U.S. Fish & Wildlife Service

FLOW RECOMMENDATIONS TO BENEFIT ENDANGERED FISHES IN THE COLORADO AND GUNNISON RIVERS

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FLOW RECOMMENDATIONS TO BENEFIT ENDANGERED FISHES IN THE COLORADO AND GUNNISON RIVERS

Recovery Program Project Number 54

Final Report

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NOTATION

Throughout this document, a combination of English and metric measurements are used according to their predominate usage for specific data categories. English equivalents are used to identify distances along the Colorado and Gunnison rivers (miles) and for measurements related to river flow (cubic feet per second [cfs]) or water volume (acre-feet [af]). English measurements for these parameters were used in this document because of their common usage. For example, river flows are reported by the U. S. Geological Survey (USGS) in cfs, and reporting flow recommendations in metric units would require reconversion to cfs before they would be meaningful to many readers (e.g., dam operators and water users). Metric units are most commonly used for biological work associated with the native fishes, and they were retained for that purpose in this report.

<u>Abbreviations, Acronyms, Units of Measure</u>

ac	acres
af	acre-feet
ANCOVA	analysis of covariance
ANOVA	analysis of variance
°C	degrees centigrade
CDOW	Colorado Division of Wildlife
cfs	cubic feet per second
CI	confidence interval
cm	centimeter
CPE	catch-per-unit-effort
CREDA	Colorado River Energy Distributors Association
CRSP	Colorado River Storage Project Act
CWCB	Colorado Water Conservation Board
day	d
DTE	depth to embededness
ESA	Endangered Species Act of 1973 (as amended)
ft	feet
g	gram
ISMP	Interagency Standardized Monitoring Program
m	meters
m^2	square meters
maf	million acre-feet
mg	microgram
mi	mile
mi^2	square miles
mm	millimeter
NRCS	Natural Resources Conservation Service
Q_b	bankfull discharge
Q_c	critical discharge = initial motion
$Q_{1.5}$	river flow with a recurrence interval of 1.5 years.
RM	River Mile: Gunnison River — measured as miles upstream from confluence with the Colorado River; Colorado River — measured as miles upstream from confluence with the Green River.
Reclamation	U.S. Bureau of Relamation.
Recovery Program	Upper Colorado River Endangered Fish Recovery Program
Service	U.S. Fish and Wildlife Service
SOW	Scope of Work
SWA	State Wildlife Area
UDWR	Utah Division of Wildlife Resources
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
USNPS	U.S. National Park Service
WAPA	Western Area Power Administration
WP	Wetland Preserve
yr	year
YOY	young of the year

NOTATION (Continued)

Definitions

critical habitat	Specific areas defined under section 3(5)(A) of the Endangered Species Act that are determined by the Secretary of Interior to be essential for the conservation of the species. Critical habitat for the four endangered fishes considered herein was designated in 1994 (Table A.1;USFWS 1994).
historical habitat	Habitat occupied by one or more of the endangered fishes at the time of westward migration by European settlers.

ACKNOWLEDGMENTS

Analyses by K. LaGory (Argonne National Laboratory) and G. Roehm (USFWS) were important to development of final flow recommendations. Hydrologists from Reclamation, USNPS, USFWS, and the University of Colorado assisted with data compilation and analysis, and provided advice on analysis techniques — J. Pitlick, C. Stanton, J. Ozga, R. Thomason, M. Wondzell, G. Smith, and P. Fiedler. Reviews by K. LaGory, R. Muth, G. Roehm, J. Lyons, D. Propst, L. Poff, B. Trush, R. Strand, T. Chart, D. Osmundson, J. Pitlick, S. McCall, B. Burdick, R. Seaholm, T. Pitts, and B. Davis improved earlier versions of this report. M. Steves and D. Mosley of Reclamation produced the maps.

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EXECUTIVE SUMMARY

The upper Colorado River subbasin (the Colorado River and its major tributaries upstream from its confluence with the Green River; the upper Colorado River basin includes all tributaries upstream from Lee Ferry, Arizona) historically supported populations of four native fishes — humpback chub *Gila cypha*, bonytail *G. elegans*, Colorado pikeminnow *Ptychocheilus lucius,* and razorback sucker *Xyrauchen texanus* — that are currently listed as endangered under the 1973 Endangered Species Act (ESA), as amended. Self-sustaining, wild populations of Colorado pikeminnow and humpback chub still occur in the subbasin, but wild razorback suckers have not been collected since 1995 and wild bonytails have been extirpated. Repatriation programs are underway for razorback sucker and bonytail.

These four species are threatened with extinction because of many factors including habitat loss from dike construction, riparian encroachment in the main channel, and construction of water-diversion structures that restrict movement; regulation of river flow, water temperature, and sediment regimes through construction of large reservoirs; introduction of nonnative fishes that are predators or competitors of the native species; and other human-induced perturbations. One of the most dramatic of these changes has been the alteration of flow regimes by tributary and mainstem reservoirs. These reservoirs inundate large areas of riverine habitat creating lentic habitat, which is often stocked with nonnative fishes. Riverine habitats remain downstream of the dams, but are modified by water-release patterns that alter temperature regimes, increase base flows, and decrease peak flows. An equally important change has been the introduction of more than 42 nonnative fishes into the upper Colorado River basin; 21 of these introduced species coexist with one or more of the endangered fishes in at least part of their range in the upper Colorado River subbasin.

Recovery of the endangered fishes in the upper Colorado River basin is being addressed by the Upper Colorado River Endangered Fish Recovery Program (Recovery Program). The Recovery Program was initiated under a Cooperative Agreement signed by the Governors of Colorado, Utah, and Wyoming; the Secretary of the Interior; and the Administrator of Western Area Power Administration in 1988. It is a coordinated effort of State and Federal agencies, water users, energy distributors, and environmental groups that functions under the general principles of adaptive management (i.e., management actions are identified, implemented, evaluated, and revised based on results of research and monitoring). The Recovery Program operates in compliance with State and Federal laws related to the Colorado River system, including State water law, interstate compacts, and Federal trust responsibilities to American Indian tribes, thereby recognizing existing water rights. The recovery goals for the endangered fishes require that habitat (including flow regimes necessary to restore and maintain required environmental conditions) necessary to provide adequate habitat and sufficient range for all life stages to support recovered populations be provided and legally protected.

The Aspinall Unit (Blue Mesa, Morrow Point, and Crystal reservoirs) was built in the upper Gunnison River prior to passage of ESA. Although the Aspinall Unit is located upstream from habitat historically occupied by the endangered fishes, its operation changed the flow regime of the Gunnison and Colorado rivers within what is now critical habitat for these species. The effect of these dams on the endangered fishes was not considered before they were built; however, operation of these reservoirs continues to affect the four endangered fishes and consultation under section 7 of ESA is therefore required.

The Aspinall Unit investigations were a group of studies designed to determine the effects of operation of these reservoirs on the endangered fishes and to provide the biological basis for flow recommendations in the Colorado and Gunnison rivers to benefit these species. These studies were designed to:

1. Track the reproductive success of endangered fish and other species in the Colorado and Gunnison rivers, and determine the relationship between physical variables, biological variables, and spawning success of endangered fish and other fish species;

2. Evaluate recruitment of endangered fish from age 0 to subsequent life history stages and determine the relationship between seasonal parameters and survival of young fish;

3. Monitor the relative abundance and population structure of endangered fishes and sympatric species to acquire information on interactions among species, and how various physical parameters may differentially affect species;

4. Determine the relationship between quality and quantity of important habitat types and seasonal flows of various levels; and

5. Establish the relationship between geomorphology and fish habitat and how these factors influence the distribution of the endangered fishes.

Because bonytails are extirpated from the upper basin, studies concentrated on humpback chub, Colorado pikeminnow, and razorback sucker. The Aspinall Unit investigations were conducted in the Gunnison and Colorado rivers, but relevant information on relationships among the endangered fishes and their habitat requirements were also available from the San Juan and Green River basins. This report summarizes and integrates results from studies conducted as part of the Aspinall Unit investigations and other relevant information to produce flow recommendations for the Gunnison River and the Colorado River downstream from their confluence that will benefit the four endangered fishes.

Monitoring population responses of the endangered fishes to different flow regimes is difficult because of their long generation times. However, relationships between reproductive success of Colorado pikeminnow and humpback chub and river flow were established for the Colorado River. Reproductive success of both species was highest in years when peak spring flows in the Colorado River downstream of the Gunnison confluence ranged from 30,000–40,000 cfs. Antecedent flows were also important predictors of Colorado pikeminnow reproductive success. Reproductive success of razorback sucker was not monitored in the Colorado River, but successful reproduction in the Green River was associated with flows sufficient to inundate floodplains and provide warm, food-rich environments for growth and survival of larval fish. Successful reproduction of these species was associated with flows sufficient to clean cobble bars of fine sediments and provide sediment-free interstitial spaces for incubation of eggs. Increased volume of interstitial spaces was also associated with increased primary and secondary production in the Colorado and Gunnison rivers. Abundance of three nonnative cyprinids (fathead minnow *Pimephales promelas*, red shiner *Cyprinella lutrensis*, sand shiner *Notropis stramineus*) was reduced in years with higher than average spring runoff. These three species are very abundant in some reaches and may prey on or compete with young of the endangered fishes, especially Colorado pikeminnow. Reduced abundance was temporary, but it may have reduced predation or competition and allowed for increased survival of young Colorado pikeminnow in some years.

The endangered fishes use a variety of habitats depending on season and species. Adult Colorado pikeminnow and razorback sucker prefer braided reaches that offer a suite of habitats in proximity to one another. Humpback chub are restricted to canyon-bound reaches and used eddies and pools during most of the year. Inundated floodplains provide warm, food-rich environments for adult Colorado pikeminnow and razorback sucker in addition to being critical for survival of larval razorback sucker. Young-of-the-year (YOY) Colorado pikeminnow are dependent on backwaters in the lower Colorado River for nursery habitat.

Movement of fine sediment through the Colorado and Gunnison rivers is critical to creation and maintenance of endangered-fish habitat. Flows equal to or greater than ½ bankfull discharge carry 65–75% of the sediment load of the Colorado and Gunnison rivers. Flows equal to or greater than bankfull discharge create and maintain in-channel features such as pools or side channels and provide inundated floodplains. Bankfull discharge also moves sediments to create and maintain backwaters, but low, stables flows are necessary to make backwaters available to YOY Colorado pikeminnow following the summer spawning period. Overall, a more naturally shaped hydrograph is necessary to create and maintain habitats for the endangered fishes and to provide needed habitats at the correct time.

Flow recommendations for the Colorado and Gunnison rivers were developed using a lines-of-evidence approach similar to that used to develop flow recommendations for the Green River (Muth et al. 2000). Specific relationships between biological response and river flow were used to quantify the underlying cause for the biological response; e.g., sediment transport that improved hatching success or increased primary production. Flows that create and maintain riverine habitats that are critical to the endangered fishes (e.g., backwaters or floodplains) were also considered in developing the recommendations. The fundamental basis of flow recommendations for the Colorado and Gunnison rivers reflect general guidelines for river restoration proposed by experts in the field; partial restoration of natural functions that benefit the riverine ecosystem were hypothesized to benefit the endangered fishes as well.

The goal of these recommendations is to provide the annual and seasonal patterns of flow in the Gunnison River and in the Colorado River downstream from their confluence to enhance populations of the four endangered fishes. The specific objectives were developed to create and maintain the variety of habitats used by all life stages of the four endangered fishes:

- Provide habitats and conditions that enhance gonad maturation and provide environmental cues for spawning movements and reproduction;

- Form low-velocity habitats for adult staging, feeding, and resting areas during snowmelt runoff;

- Inundate floodplains and other off-channel habitats at the appropriate time and for an adequate duration to provide warm, food-rich environments for fish growth and conditioning, and to provide river-floodplain connections for restoration of ecosystem processes;

- Restore and maintain in-channel habitats used by all life stages: (1) spawning areas for adults, (2) spring, summer, autumn and winter habitats used by subadults and adults, and (3) nursery areas used by larvae, YOY, and juveniles; and

- Provide base flows that promote growth and survival of young fish during summer, autumn, and winter.

Because historical river flows were dependent on water availability, flow recommendations were developed for six hydrologic categories that correspond to unregulated April–July inflow based on the 1937–1997 period of record: Dry (90–100% exceedance); Moderately Dry (70–90% exceedance); Average Dry (50–70% exceedance); Average Wet (30–50% exceedance); Moderately Wet (10–30% exceedance); and Wet (0–10% exceedance). Flow recommendations are for the Gunnison River at the USGS river gage near Grand Junction, Colorado (09152500) and for the Colorado River at the USGS river gage near the Colorado-Utah state line (09163500). Spring peak-flow recommendations for both rivers correspond to specific recommendations by Pitlick et al. (1999) to maintain and improve in-channel habitat in both rivers. Peak-flow recommendations include two components: (1) threshold levels corresponding to ½ bankfull discharge and bankfull discharge and (2) the number of days (duration) that flows should equal or exceed these levels. In addition, recommended durations are presented as a range of days to provide flexibility to river managers. In general, spring flows recommended for the dry categories provide small peaks used as spawning cues by endangered fish, but contribute little to habitat maintenance; spring flows recommended for average categories promote scouring of cobble and gravel bars and provide localized flooding of short duration; and spring flows for the wet categories promote wide-spread scouring of cobble and gravel bars, flushing of side channels, removal of encroaching vegetation, and inundation of floodplain habitats. Base-flow recommendations also vary with hydrologic category and are designed to allow fish movement among river segments and to provide maximum amounts of warm, quiet-water habitats to enhance growth and survival of young endangered fish.

These flow recommendations were developed using the best information currently available; however, it is recognized that uncertainties exist. Biological and physical uncertainties are described and additional studies are proposed. These recommendations should be implemented using adaptive management, with guidance provided by a technical team of biologists and hydrologists familiar with the Gunnison and upper Colorado rivers. Modifications should be made as more information is gained.

1.0 INTRODUCTION

1.1 Background

The upper Colorado River subbasin (the Colorado River and its major tributaries upstream from its confluence with the Green River; Figure 1.1 [the upper Colorado River basin includes all tributaries upstream from Lee Ferry, Arizona]) historically supported populations of four native fishes — humpback chub *Gila cypha*, bonytail *G. elegans*, Colorado pikeminnow *Ptychocheilus lucius* (formerly Colorado squawfish [Nelson et al. 1998]), and razorback sucker *Xyrauchen texanus* — that are currently listed as endangered under the Endangered Species Act, as amended (ESA; USFWS 2000). Self-sustaining populations of Colorado pikeminnow (river wide; Osmundson and Burnham 1998) and humpback chub (Black Rocks and Westwater Canyon; Kaeding et al. 1990; Chart and Lentsch 1999a) persist in the subbasin. However, the wild razorback sucker population has declined (Osmundson and Kaeding 1991; Burdick 1992) and the last wild razorback sucker was captured in 1995 (M. Baker, personal communication). An augmentation program for razorback sucker began in 1995, and about 63,000 razorback suckers have been stocked since then (Burdick 2002). The bonytail is extirpated from the upper Colorado River, but one of the last individuals captured there was found in Black Rocks near the Colorado-Utah border (Kaeding et al. 1986). A reintroduction program began for bonytail in 1996, and about 86,000 bonytails have been stocked into the Colorado River since then (Badame and Hudson 2000). Because of past and present distribution of these species, substantial parts of the upper Colorado River and its major tributary the Gunnison River were designated as critical habitat for one or more of the four species. Critical habitat for the four endangered fishes in the upper Colorado River subbasin includes the Colorado River from its confluence with the Green River upstream to Rifle, Colorado and the Gunnison River from its mouth upstream to its confluence with the Uncompahgre River (USFWS 1994; Table A.1).

Humpback chub, bonytail, Colorado pikeminnow, and razorback sucker are threatened with extinction because of many factors including habitat loss from dike construction, riparian encroachment in the main channel, and construction of movement barriers such as water diversions; alteration of natural river flow, water temperature, and sediment regimes through construction of large reservoirs; introduction of nonnative fishes that are predators or competitors of native species; and other human-induced perturbations (Miller 1961; Minckley and Deacon 1968; Minckley 1973; Holden and Stalnaker 1975; Maddux et al. 1993; Stanford 1994). The most dramatic physical change has been the alteration of natural flow regimes by reservoirs constructed on the tributaries and mainstem rivers of the basin. The reservoirs inundate large areas of riverine habitat and replace it with lentic habitat, which is often stocked with nonnative fishes. Riverine habitat remains downstream of the dams, but it is modified by water-release patterns that alter temperatures, increase base flows, and decrease peak flows (e.g., Vanicek et al. 1970; Ligon et al. 1995; Collier et al. 1996). An equally important change has been the introduction of more than 42 nonnative fishes into the upper Colorado River basin (Tyus et al. 1982); 21 of these introduced species coexist with one or

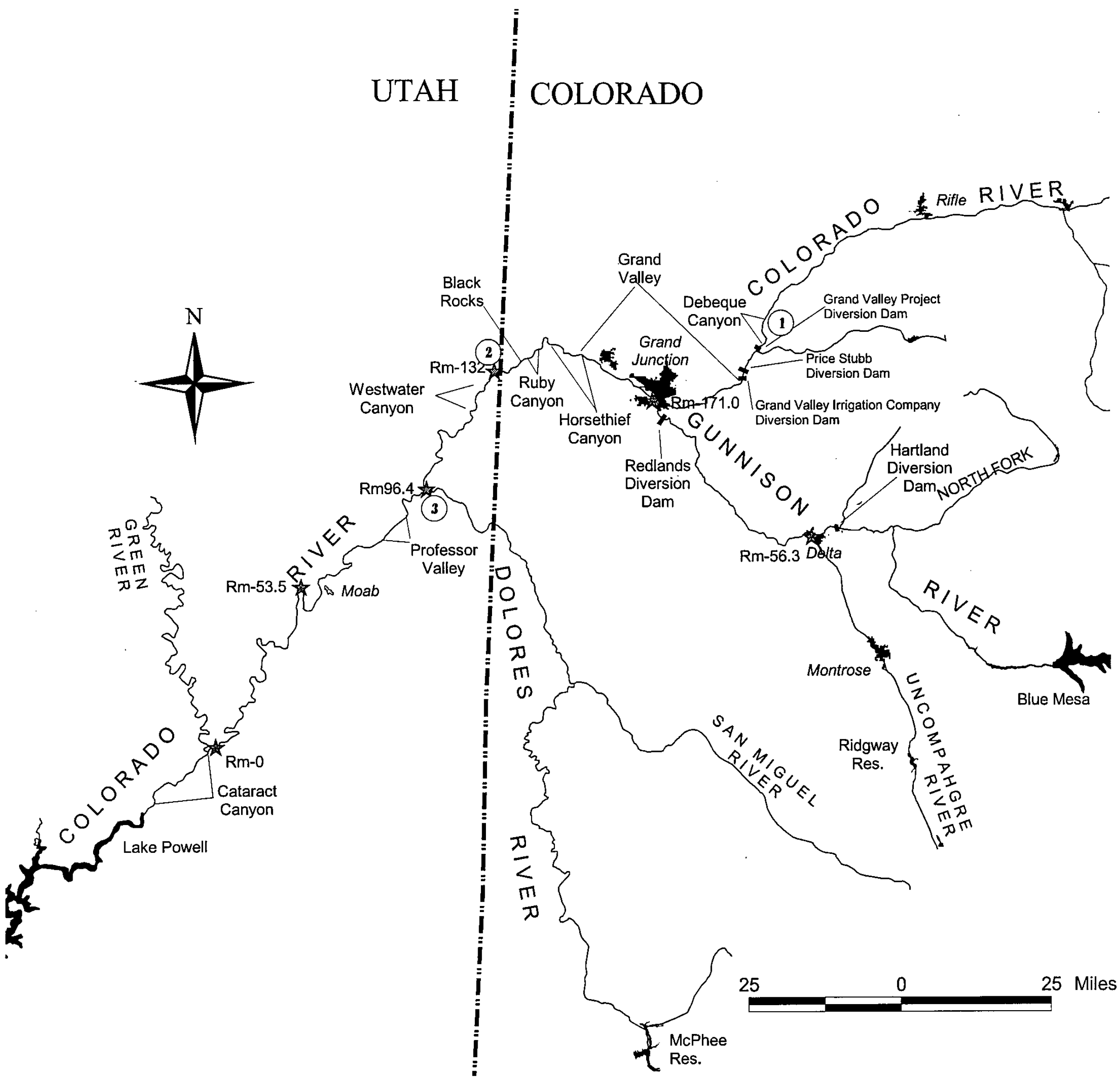

FIGURE 1.1. — Overview of the upper Colorado and Gunnison rivers. River mile 0 for the Colorado River is the mouth of the Green River and RM 0 for the Gunnison River is its mouth. The Grand Valley portion of the Colorado River is often divided into two reaches because of influences of diversion dams and the Gunnison River: (1) 15-mile reach (Grand Valley Irrigation Company Dam to mouth of Gunnison River, RM 185–171) and (2) 18-mile reach (Gunnison River downstream, RM 171–153). USGS river gages on the Colorado River mentioned in the text: ① Colorado River near Cameo, Colorado (09095500); ② Colorado River near Colorado-Utah state line (09163500); and ③ Colorado River near Cisco, Utah (09180500).

more of the endangered fishes in at least part of their range in the upper subbasin (Section 3.1).

Recovery of the endangered fishes in the upper Colorado River basin is being addressed by the Upper Colorado River Endangered Fish Recovery Program (Recovery Program; Wydoski and Hamill 1991). The Recovery Program was initiated under a Cooperative Agreement signed by the Governors of Colorado, Utah, and Wyoming; the Secretary of the Interior; and the Administrator of Western Area Power Administration (WAPA) in 1988. It is a coordinated effort of State and Federal agencies, water users, energy distributors, and environmental groups that functions under the general principles of adaptive management (i.e., management actions are identified, implemented, evaluated, and revised based on results of research and monitoring). The Recovery Program operates in compliance with State and Federal laws related to the Colorado River system, including State water law, interstate compacts, and Federal trust responsibilities to American Indian tribes, thereby recognizing existing water rights. The recovery goals for the endangered fishes require that habitat (including flow regimes necessary to restore and maintain required environmental conditions) necessary to provide adequate habitat and sufficient range for all life stages to support recovered populations be provided and legally protected.

Although many private irrigation projects already existed, development of water storage in the Colorado River basin began in earnest during the 1930s with construction of several projects by the U.S. Bureau of Reclamation (Reclamation). Reservoir construction in the upper basin increased dramatically in the 1950s and 1960s with passage of the Colorado River Storage Project Act (CRSP) that authorized construction of several large dams on major rivers of the upper Colorado River basin. Three of these dams (Glen Canyon, Flaming Gorge, and Navajo) were built within habitat historically occupied by at least one of the listed species. Three additional dams (Blue Mesa, Morrow Point, and Crystal) were built on the upper Gunnison River as part of the Aspinall Unit (Figure 1.2). Although located upstream from reaches historically inhabited by endangered fishes, operation of the Aspinall Unit dramatically changed the flow regime of the Colorado and Gunnison rivers within what is now critical habitat. Because CRSP was authorized before passage of ESA, the effect of these dams on the native-fish community was not considered before they were built. However, operations of the Aspinall Unit and other CRSP reservoirs continue to affect the endangered fishes, and consultation under Section 7 of ESA is required on operation of the dams. Therefore, Reclamation and the U.S. Fish and Wildlife Service (Service) began consulting on operation of these reservoirs in the early 1980s. In the upper basin, the first consultation was directed at operation of Flaming Gorge Dam, which resulted in a biological opinion that concluded that historical operation of the dam (i.e., pre 1992) jeopardized the continued existence of the endangered species in the Green River (USFWS 1992). The biological opinion outlined a series of reasonable and prudent alternatives that were designed to offset the impacts of dam construction and operation. Among other things, the reasonable and prudent alternatives included modifying dam operation to more closely mimic a natural hydrograph and conducting a series of studies designed to monitor the effect of the new flow regime on endangered fishes (Muth et al. 2000). A second biological opinion on operation of Flaming Gorge Dam will be prepared in the near future.

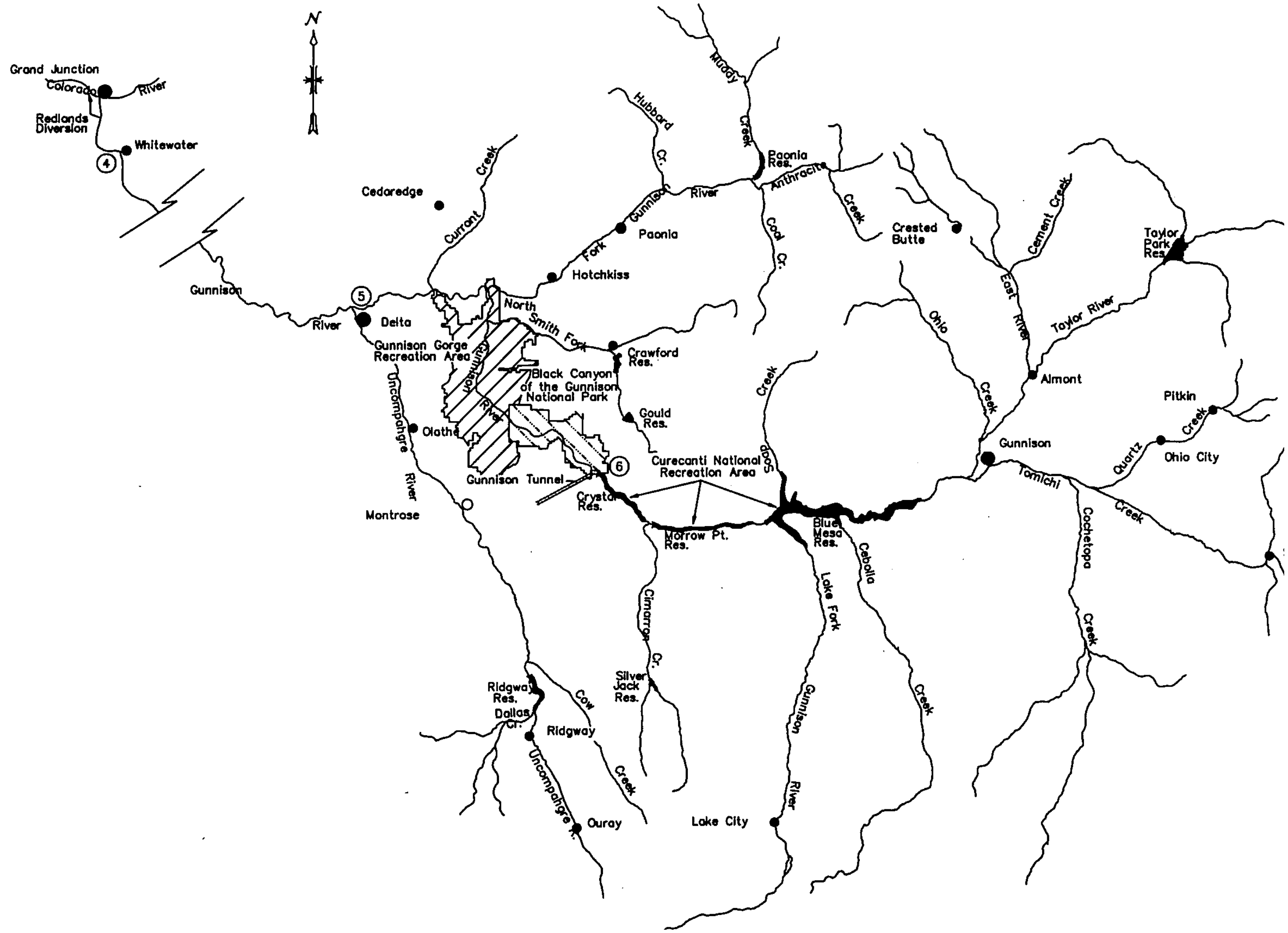

FIGURE 1.2. — Overview of the Gunnison River basin. River mile 0 is the confluence with the Colorado River. USGS river gages on the Gunnison River mentioned in the text: ④ Gunnison River near Grand Junction, Colorado (09152500); ⑤ Gunnison River at Delta, Colorado (09144250); ⑥ Gunnison River below Gunnison Tunnel, Colorado (09128000).

Although a biological opinion has not been done for the Aspinall Unit, opinions on two more recent Reclamation projects in the upper Colorado River subbasin have been completed: Ridgway Reservoir (Dallas Creek Project; Figure 1.2) on the Uncompahgre River, a major tributary to the Gunnison River, and McPhee Reservoir (Dolores Project; Figure 1.1) on the Dolores River, a major tributary to the Colorado River (USFWS 1979, 1980a). Biological opinions for the Dallas Creek and Dolores projects identified a combined total of 148,000 af of water depletions associated with the two projects.[1] The opinions also specified that the depletions would be made up by a larger (but unspecified) Reclamation reservoir in the upper Colorado River subbasin. Blue Mesa Reservoir in the largest reservoir in the subbasin and is the most likely source of water to replace depletions associated with Ridgway and McPhee reservoirs.

A biological opinion on the implementation of recovery actions and water depletions in the upper Colorado River subbasin upstream from the Gunnison River confluence was recently completed (USFWS 1999). This "programmatic" opinion addresses all existing water depletions and 120,000 af of new depletions to the Colorado River upstream from the Gunnison River. The biological opinion concludes that with implementation of recovery actions, the subject water depletions are not likely to jeopardize the continued existence of the endangered fishes or adversely modify critical habitat. Implementation of recovery actions identified in the opinion will benefit endangered fishes in the Colorado River up- and downstream from the Gunnison River.

In 1991, the Service, Reclamation, and other cooperators participating in the Recovery Program began a process that was designed to produce a biological opinion on operation of the Aspinall Unit. The first phase of that process was to design a series of studies that would assist in developing flow recommendations for the Gunnison River and for the Colorado River downstream from their confluence. This document summarizes the results of those investigations and describes biologically based flow recommendations that will assist in recovery of the four endangered fishes.

1.2 Overview of Aspinall Unit Investigations

In response to directions from the Recovery Program, McAda and Kaeding (1991a) developed a series of hypotheses that addressed effects of flow regulation on endangered fishes in the Colorado and Gunnison rivers (Table A.2). Studies designed to test these hypotheses were developed by investigators from the Service, Colorado Division of Wildlife (CDOW), Utah Division of Wildlife Resources (UDWR), U.S. Geological Survey (USGS), University of Colorado, and private contractors. These studies were conducted as a group of investigations funded by the Recovery Program under a scope of work entitled "A five year

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[1]Depletions for the two projects are currently smaller than identified in the biological opinions. However, the Service and Reclamation positions are that modification of depletions identified in the biological opinions and reserved for the endangered fish requires reinitiation of consultation under ESA, which is at the discretion of Reclamation.

study to investigate the effects of Aspinall Unit operations on endangered fishes in the Colorado and Gunnison rivers." Field work was conducted from 1992 through 1996, with individual studies requiring anywhere from 2 to 5 yr of field work to complete. Although most field work was completed by 1996, data analysis and report writing continued into 1999 and 2000 for some investigations.

1.2.1 Study Area

The study area for the Aspinall Unit investigations included all river reaches in the upper Colorado River subbasin occupied by at least one of the four endangered fishes — the Colorado River between Grand Valley Irrigation Company Diversion Dam near Grand Junction, Colorado downstream to its confluence with the Green River and the Gunnison River from Hartland Diversion Dam near Delta, Colorado downstream to its confluence with the Colorado River (Figures 1.1 and 1.2). Studies concentrated on different sections of the two rivers depending on emphasis of the investigations.

1.2.2 Study Objectives and Approach

The overall goal of studies conducted under the Aspinall Unit investigations was to evaluate the biological and physical responses of the Colorado and Gunnison River ecosystems to test flows from the Aspinall Unit. These investigations had five major objectives:

1. Track the reproductive success of endangered fish and other species in the Colorado and Gunnison rivers, and determine the relationship between physical variables, biological variables, and spawning success of endangered fish and other fish species;

2. Evaluate recruitment of endangered fish from age 0 to subsequent life history stages and determine the relationship between seasonal parameters and survival of young fish;

3. Monitor the relative abundance and population structure of endangered fishes and sympatric species to acquire information on interactions among species, and how various physical parameters may differentially affect species;

4. Determine the relationship between quality and quantity of important habitat types and seasonal flows of various levels; and

5. Establish the relationship between geomorphology and fish habitat and how these factors influence distribution of the endangered fishes.

The end product of these investigations was to produce biologically based, seasonal flow recommendations for the Gunnison and Colorado (downstream from its confluence with the Gunnison River) rivers that will benefit endangered and native fish species.

Studies conducted under the Aspinall Unit investigations addressed the hydrology and geomorphology of the Colorado and Gunnison rivers as well as the life history and ecology of the endangered fishes. Biological studies emphasized Colorado pikeminnow and humpback chub because razorback sucker and bonytail are so rare in the upper Colorado River subbasin that they are impossible to study. These efforts included short-term studies that addressed specific hypotheses as well as long-term studies that incorporated data from investigations that preceded the Aspinall Unit effort such as the Interagency Standardized Monitoring Program (ISMP; McAda et al 1994b). Studies conducted under the Aspinall Unit investigations are listed in Table 1.1, and their results are summarized in Chapters 2 and 3. Primary conclusions of the different studies and their relationship to the hypotheses presented by McAda and Kaeding (1991a) are presented in Table A.3.

Other studies conducted on endangered fishes of the upper Colorado River basin were also utilized in this report. In particular, parallel investigations were conducted in the San Juan and Green River basins during the same period as the Aspinall Unit investigations (Holden 1999; Muth et al. 2000). Because these investigations were also directed at determining the effect of river flows on the endangered fishes, many of their results are appropriate to developing flow recommendations for the Colorado and Gunnison rivers. Although specific relationships identified for the Green and San Juan rivers do not necessarily apply to the Colorado and Gunnison rivers, the basic concepts underlying those relationships are useful to an understanding of the effects of river flow on the endangered fishes. Results from these studies were especially important for razorback sucker because they are so rare in the upper Colorado subbasin. Finally, a large body of literature is available on relationships between flow regime and structure and function of a river ecosystem. This information was also utilized when appropriate to understand relationships between flow and endangered fishes in the Colorado and Gunnison rivers.

As noted previously, factors other than modified flow regimes contributed to the decline of the four endangered fishes. However, this document is intended only to provide flow recommendations for the Colorado and Gunnison rivers — it does not address other factors responsible for decline of endangered fishes. The Recovery Program is using a multifaceted approach for recovering these species and has components addressing control of nonnative species, reintroduction and augmentation of extirpated and declining populations, and habitat improvement or restoration. Activities from each of these major categories are ongoing in the Colorado and Gunnison rivers, but are only discussed in this document when pertinent to developing flow recommendations. Other material produced by the Recovery Program discusses these activities and documents the interrelationships among many components of the cooperative efforts to recover these four endangered species (e.g., nonnative fish control — Lentsch et al. 1996, Tyus and Saunders 1996; propagation — Burdick 1992, Nesler 1998, Hudson et al. 1999; habitat restoration — USBR and USFWS 1998).

TABLE 1.1. — Studies included in the Aspinall Unit Investigations.

	Study Number and Title[a]	Citation
42	Ichthyofaunal survey (with emphasis on distribution and abundance of endangered fish) in the Gunnison River from Delta, Colorado to the Redlands Diversion Dam.	Burdick 1995
43	Evaluation of Gunnison River flow manipulation upon larval production of Colorado pikeminnow in the Colorado River.	Anderson 1999; Trammell and Chart 1999a
44	Evaluation of Gunnison River flow manipulation upon availability and quality of nursery habitat for Colorado pikeminnow in the Colorado River.	Trammell and Chart 1999b
44b	Changes in channel morphology of the Colorado and Gunnison rivers.	Pitlick et al. 1999
45	Flow effects on young-of-the-year Colorado pikeminnow and sympatric species.	McAda and Ryel 1999
46	Flow effects on humpback chub populations in Westwater Canyon.	Chart and Lentsch 1999a
47	Quantification of available habitat in the Gunnison River in relation to test flows released from the Aspinall Unit.	McAda and Fenton 1998
48	Impact of flows and geomorphology on food web dynamics of the Colorado River native fish community: a river-wide, interdisciplinary, ecosystem approach to flow recommendations.	Lamarra 1999; Osmundson 1999; Pitlick and Cress 2000

[a] All studies referenced have been accepted as final by the Recovery Program.

1.2.3 Aspinall Unit Operations During the Study Period

The Aspinall Unit investigations were conducted from 1992 to 1998 in conjunction with modifications to historical release patterns from the Aspinall Unit. Prior to this study, standard operating procedure was to calculate the amount of water entering the reservoir in spring that exceeded the volume necessary to fill Blue Mesa Reservoir and release it gradually over the spring and summer months. During the study period, release of this excess water was reconfigured to provide a maximum release at Crystal Reservoir (the lowest reservoir on the system) of 4,000 cfs (2,000 cfs through the turbines and 2,000 cfs through the bypass tubes) for at least a short period each spring. The reshaping of the hydrograph occurred primarily in low to average water years when more of the inflow would have been stored and released more slowly under historical operations. Historical operations often resulted in releases of 4,000 cfs and greater during above average years because there is insufficient storage to contain inflow to the Aspinall Unit under those conditions. Highest flows occurred when Blue Mesa releases in conjunction with tributary input to Morrow Point and Crystal reservoirs exceeded their limited storage capacity, which forced water over the spillway at Crystal Reservoir. Detailed presentations of historical operation of the Aspinall Unit and specific operations during the study period are presented in Sections 2.1.3 and 2.1.4.

McAda and Kaeding (1991a) outlined a series of target flows for the study period that provided a variety of runoff patterns to facilitate comparisons among years. To a large extent, target flows could not be varied independently of environmental conditions because they were heavily dependent on snow pack in the upper Colorado and Gunnison rivers. Target flows were measured at the USGS gage near Grand Junction, Colorado (09152500), so Reclamation had to coordinate releases from the Aspinall Unit to coincide with maximum runoff in the rest of the Gunnison River basin. The proposed spring flows ranged from relatively high to relatively low with targets for spring peaks (mean-daily flow on the highest day of the year) of between 2,000 and 5,000 cfs in 1 yr, between 5,000 and 10,000 cfs in 1 yr, above 12,000 cfs in 2 yr, and above 15,000 cfs in 1 yr. The study occurred during a wet period and all but the lowest target flows were met during the 5-yr period. Peak flows for the study period were: 6,360 cfs in 1992; 20,500 cfs in 1993; 6,040 cfs in 1994; 17,300 cfs in 1995; and 7,670 cfs in 1996. In addition, supplemental data were collected in 1997 with a peak flow of 12,000 cfs and in 1998 with a peak flow of 9,360 cfs.

1.2.4 Development of Integrated Flow Recommendations

Monitoring population responses of endangered fishes to different flow regimes is difficult because of the long generation times of these species. It is unrealistic to expect population responses in as short a time frame as encompassed by the Aspinall Unit studies. Also, it is impossible to conduct controlled experiments in an environment as complex as the Colorado and Gunnison rivers; therefore, clear-cut cause and effect relationships could not be established and specific biological responses could not be directly attributed to one variable alone. Many variables are interrelated and a suite of variables may contribute to an observed response. Nonetheless, river flow is the dominating influence in a river system (e.g., Stanford et al. 1996) and it controls changes in the physical environment that affect the endangered fishes.

Flow recommendations for the Colorado and Gunnison rivers were therefore developed using a lines-of-evidence approach similar to that used to develop flow recommendations for the Green River (Muth et al. 2000). Specific relationships between biological response and river flow were used to quantify the underlying cause for the biological response (e.g., sediment transport that improved hatching success or increased primary production). Creation and maintenance of riverine habitats that are critical to the endangered fishes (e.g., backwaters or floodplains) also weighed heavily in the recommendations. The fundamental basis of flow recommendations for the Colorado and Gunnison rivers reflect general guidelines for river restoration proposed by recognized experts (e.g., Stanford 1994; Stanford et al. 1996; Poff et al. 1997; Richter et al. 1997; Sparks 1997). Partial restoration of natural functions through mimicry of a natural hydrograph benefits the riverine ecosystem and was hypothesized to benefit the four endangered fishes as well.

2.0 HYDROLOGY AND GEOMORPHOLOGY OF THE COLORADO AND GUNNISON RIVERS

2.1 HYDROLOGY

2.1.1 Overview

***Colorado River*. —** The Colorado River originates in Rocky Mountain National Park in north-central Colorado and flows generally southwesterly across Colorado until it exits the state downstream of Grand Junction. Total drainage area is about 17,843 mi^2 at the Colorado-Utah border. Drainage area upstream from the mouth of the Gunnison River, its largest tributary, is about 8,753 mi^2. Major tributaries in that region include the Blue, Eagle, Roaring Fork, and Fraser rivers and Plateau, Roan, Parachute, and Rifle creeks. The Colorado River and its major tributaries gain most of their water from snow that accumulates in mountains of the subbasin; most runoff occurs during spring snow melt. Summer thunderstorms raise river levels briefly, but contribute only a small percentage of total runoff. An annual average of 4.982 maf (range, 1.601–9.993 maf) of water passed by the USGS gage at the Colorado–Utah state line during 1977–1996. About 40.5% of this volume comes from the Gunnison River basin (see next section). This value includes only water passing the gage and does not include upstream depletions. Based on estimates for 1986–1990, an annual average of 1.363 maf (range, 1.203–1.536 maf) of water is depleted in the Colorado River subbasin above the Colorado–Utah state line (USBR 1997; Table A.4).

***Gunnison River*. —** The Gunnison River is the largest tributary to the upper Colorado River in western Colorado. It originates at the confluence of the Taylor and East rivers near Almont, Colorado and flows for about 150 mi west-northwest to its confluence with the Colorado River near Grand Junction, Colorado. Drainage area is 766 mi^2 at Almont, 3,965 mi^2 immediately downstream from the Aspinall Unit, and 7,928 mi^2 at its confluence with the Colorado River. Its two largest tributaries are the North Fork of the Gunnison River, which enters the Gunnison near Hotchkiss, Colorado, and the Uncompahgre River which enters the river near Delta, Colorado.

During 1977–1996, an annual average of 2.016 maf (range, 0.601–3.460 maf) of water passed the last USGS gage on the Gunnison River (Gunnison River near Grand Junction, 09152500). About 40.5% of the annual flow of the Colorado River at the Colorado-Utah state line came from the Gunnison River basin (Figure 2.1). About 46% of that 2.016 maf comes from upstream of the Aspinall Unit (including tributaries entering the river between Blue Mesa and Crystal reservoirs). About 32% (0.650 maf) of the total comes from tributaries between the Aspinall Unit and Delta, primarily the North Fork of the Gunnison and the Smith Fork rivers, about 12% (0.239 maf) comes from the Uncompahgre River, and an additional 9.5% (0.191 maf) comes from smaller tributaries (e.g., Roubideau and Escalante creeks) that enter the river between Delta and its mouth. An annual average of 0.336 maf of water produced upstream from the Aspinall Unit is diverted into the Uncompahgre Valley through

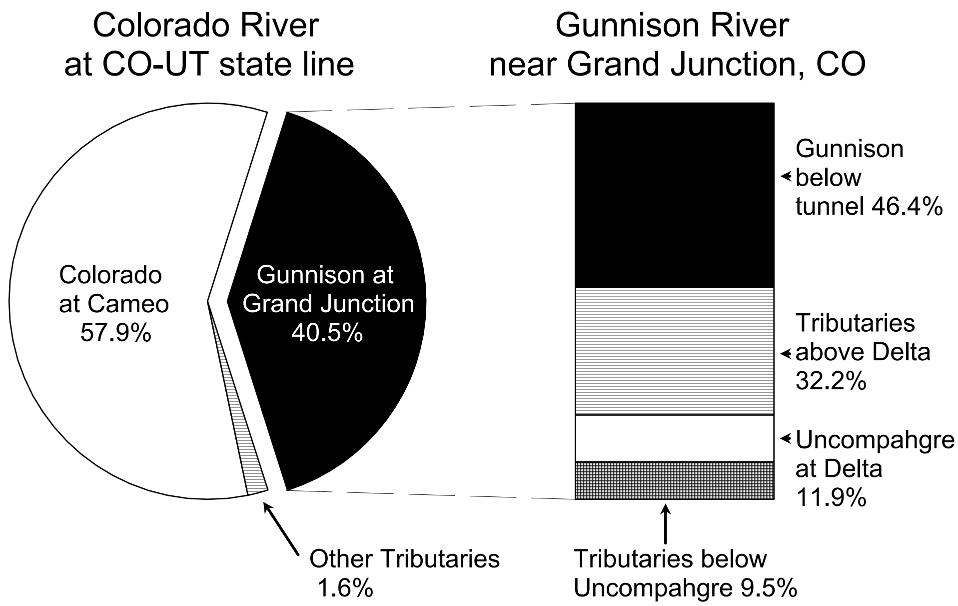


FIGURE 2.1. — Relative contribution of major tributaries to the Colorado River at the Colorado-Utah state line (USGS station number 09163500; left) and the Gunnison River near Grand Junction, Colorado (USGS station number 09152500; right). Percentages are based on average annual volume for 1977–1996: Gunnison River near Grand Junction, 2,016,000 af and Colorado River at the state line, 4,982,000 af. These values reflect water actually passing the different gages and do not include water diverted from, or depleted within the different basins (Colorado, average = 817,614 af and Gunnison, average = 545,011 af [Table A.4]). The Gunnison River below the tunnel does not include an average of about 336,000 af diverted through the Gunnison Tunnel during the irrigation season. About one half of this amount reenters the Gunnison River as irrigation return flows.

the Gunnison Tunnel immediately downstream from Crystal Reservoir during the irrigation season (USBR 1990).

The water is used for irrigation in the Uncompahgre Valley and return flows reenter the Gunnison River through the Uncompahgre River, Roubideau Creek, and other tributaries and drains. The average annual water volumes discussed above were calculated from measurements at the gages mentioned and do not account for current depletions. Based on estimates for 1986 to 1990, an annual average of 0.545 maf (range, 0.446–0.614 maf) of water is depleted in the Gunnison River basin (USBR 1997; Table A.4).

2.1.2 Water Development

Colorado River. — The first reservoirs in the upper Colorado River subbasin were constructed during the 1890s for water storage and irrigation (Liebermann et al. 1989).

Transbasin diversions to the eastern slope of the Rocky Mountains began in 1892 when the Grand River Ditch was constructed in the headwaters of the Colorado River near Grand Lake (Liebermann et al. 1989). Many reservoirs and diversions have been constructed since then (Figure 2.2; Table A.5). The Alva B. Adams Tunnel/Lake Granby diversion and storage system is the largest transbasin diversion in the upper Colorado River subbasin (Liebermann et al. 1989). The Adams Tunnel and Shadow Mountain Reservoir were completed in 1947, but major diversions did not begin until Lake Granby (the largest reservoir in the Colorado River subbasin upstream from the mouth of the Gunnison River) was completed in 1950. Annual diversions through this project average about 250,000 af/yr (Liebermann et al. 1989). Other major diversion projects include Twin Lakes Tunnel (completed in 1935), Moffat Tunnel (1936), Roberts Tunnel and Dillon Reservoir (1963), Homestake Tunnel and Reservoir (1967), and Ruedi Reservoir and Boustead Tunnel (1968 and 1972, respectively; Liebermann et al. 1989). Transbasin diversions averaged less than 2,000 af/yr at the turn of the century (Lieberman et al. 1989), but have increased to an annual average of 350,000 af/yr (USBR 1997; Table A.4). Volume of transbasin diversions remain relatively constant from year to year and compose a higher percentage of the total runoff in dry years than in average or wet years.

Construction and operation of reservoirs have influenced flow patterns of the Colorado River by reducing peak spring runoff and increasing base flows during the remainder of the year. Pitlick et al. (1999) compared river flows at the USGS gage near Cameo, Colorado (09095500; the most downstream gage that does not include flows from the Gunnison River) for two periods: 1934–1949 (beginning of gage records to completion of Lake Granby) and 1950–1995. Even though substantial water development occurred during the early period, Pitlick et al. (1999) documented a statistically significant 29% decline in peak runoff from the first period to the second. Mean annual flow (average mean-daily flows for all years in category) decreased only 8% (not a significant difference) during the same period, suggesting that annual yield of the subbasin did not change dramatically. Pitlick et al. (1999) considered their estimate of the effects of water development on peak discharge to be conservative because development began before data collection began at the Cameo gage and continued through both study periods.

Osmundson and Kaeding (1991) extended the period of record back to 1902 by using data from other gages that, in combination, equaled flows that passed what became the Cameo gage. They partitioned river-flow data into 1902–1942 and 1954–1989, and showed that average peak runoff in the second period declined by 44% from the first period. Their early period preceded most water development in the subbasin, but included a portion of the 20th century that is generally considered to be wetter than most of the period of record (e.g., Meko et al. 1991). Because water development and river measurement began at about the same time, it is difficult to determine how water development alone has affected peak runoff flows by analyzing gage data. The decrease in peak runoff solely attributable to water development probably is between the estimates of Pitlick et al. (1999) and Osmundson and Kaeding (1991). However, Osmundson and Kaeding's estimate probably best reflects the overall changes in peak river flow that have occurred in the Colorado River during this century.

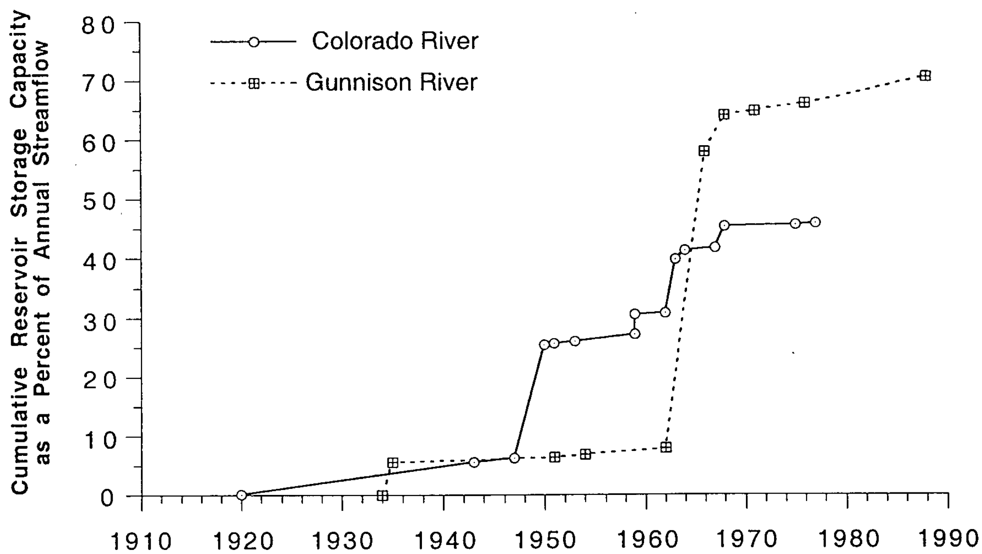


FIGURE 2.2. — Cumulative reservoir storage capacity as a percentage of average annual river flow for the Colorado River near Cameo (09095500) and the Gunnison River near Grand Junction (09152500). Figure 4 in Pitlick et al. (1999); based on data in Lieberman et al. (1989).

As further comparison, change in frequency of peak river flows for the Colorado River at the USGS gage near Cisco, Utah (09180550) for three water-development periods[2] (1914–1936, 1937–1965, and 1966–1997) is presented in Figure A.1. $Q_{1.5}$ (river flows that were equaled or exceeded in 2 out of 3 yr) for the three periods was 37,200 cfs in 1914–1936, 27,900 in 1937–1965, and 21,600 in 1966–1992 (Table A.6). $Q_{1.5}$ is often used to describe bankfull discharge for a river when specific data are not available (J. Pitlick, personal communication). Bankfull discharge in the Colorado River tends to be higher than $Q_{1.5}$, and specific values for bankfull discharge are given in Section 2.2.2.

Analyses such as those done by Osmundson and Kaeding (1991) and Pitlick et al. (1999) used average flows that occur over a wide range of snow-pack conditions and do not depict the natural variation in peak runoff that occurs in a river system. Figure 2.3 shows the relationship between peak runoff and available snow pack (depicted as unregulated inflow to the river system during April–July as estimated by the Natural Resources Conservation Service [NRCS]) for the three water-development periods. Construction of large water-development projects began in the latter part of the first period (Section 2.1.1) and continued throughout most of the second and third periods, so it is impossible to clearly depict the effect

[2]These periods are arbitrary for the Colorado River, but correspond to available data and important water-development periods in the Gunnison River.

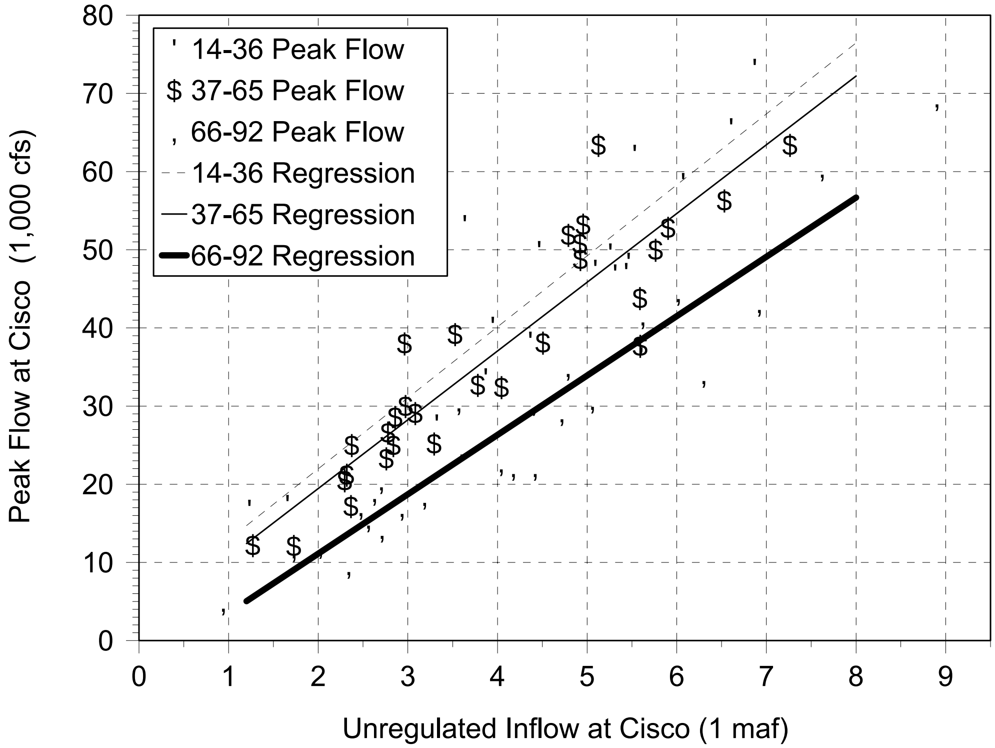


FIGURE 2.3. — Relationship of peak flow (highest mean-daily flow of the year) to unregulated April–July inflow to the Colorado River at the USGS gage near Cisco (09180500) for three periods: 1914–1936, 1937–1965, and 1965–1992. These three periods correspond to major water-development periods in the upper Colorado River subbasin, but reservoir construction occurred throughout both of the latter two periods. Limited water development also occurred prior to 1936, and the period is generally considered to have a period that was 'wetter' than most of the 20th Century. Regression lines were significant (P<0.001; 1914–1936, R^2=0.78; 1937–1965, R^2=0.80; and 1966–1992, R^2=0.92) and significantly different from each other (ANCOVA, P<0.05).

of water development on peak river flow. Nonetheless, the change in regression lines for the three periods indicate the decline in spring peaks associated with the same volume of available snow pack as water development continued through the 20th Century.

Although base flows have increased as a result of water regulation, river flows downstream from irrigation diversions can be dramatically reduced under some conditions. Three instream irrigation diversions were constructed on the Colorado River immediately upstream from the Grand Valley. The lowermost diversion (owned by Grand Valley Irrigation Company) has a senior water right under Colorado Water Law and can divert the entire flow of the river under low-water conditions. The river can be almost dewatered immediately below this dam with low-water conditions persisting until its confluence with the Gunnison River. However, the reach (referred to as the 15-mile reach) regains some volume through irrigation return flows that reenter the river within the reach. The diversion dams also block fish movement (Section 3.2.1), but the Recovery Program has built passage at the lowermost dam and is scheduled to complete fish passage at the other structures.

Minimum streamflows have been recommended for the 15-mile reach (Osmundson et al. 1995), and the Recovery Program is actively attempting to meet these flows with releases from upstream reservoirs and more efficient water management. Recovery actions identified in the programmatic biological opinion for the upper Colorado River (USFWS 1999) are addressing this problem (e.g., coordinated operation of upstream reservoirs to provide water to the reach).

Gunnison River. — Private irrigation development began in the Gunnison River basin in the late 1880s with an estimated 200,000 ac under irrigation by 1986 (Liebermann et al. 1989). Federal involvement began in 1909 with completion of the Gunnison Tunnel (Uncompahgre Project), which diverts water from the Gunnison River into the Uncompahgre River. Taylor Park Dam, on the Taylor River in the headwaters of the Gunnison River, was completed in 1937 to provide water storage for the Gunnison Tunnel. Other small projects followed, but most reservoir construction in the Gunnison River basin occurred after 1960. Total water storage in the Gunnison River basin was rather small until completion of Blue Mesa Reservoir (940,700 af total capacity; Table A.8) in 1966 which increased total storage capacity in the Gunnison basin from 9 to 60% of average annual river flow (Figure 2.2). Two other dams were subsequently added to the Aspinall Unit downstream from Blue Mesa Reservoir — Morrow Point (117,190 af) in 1968 and Crystal (25,240 af) in 1976. All three facilities are used to generate power as well as to provide water storage. Crystal (the lowermost dam and reservoir) serves as a reregulation facility to reduce river fluctuations created by abrupt changes in water releases at Blue Mesa and Morrow Point dams caused by altering power generation to match increases and decreases in power demand. The most recent reservoir in the Gunnison River basin — Ridgway (84,410 af), part of the Dallas Creek Project — was built on the Uncompahgre River in 1986.

As with the Colorado River, construction and operation of these reservoirs has had a major influence on the hydrology of the Gunnison River, with the largest impact coming from Blue Mesa Reservoir[3] (Figure 2.2). Pitlick et al. (1999) compared peak flows (mean-daily flow on the highest day of the year) from the Gunnison River (measured at the USGS gage near Grand Junction) for two periods, before (1897–1965) and after (1966–1995) construction of Blue Mesa Reservoir (Figure 2.4). Peak flow was significantly lower after completion of Blue Mesa Dam, declining 38% from a mean of 15,925 cfs in the pre-dam period to a mean of 9,887 cfs in the post-dam period. In contrast, mean annual flows (average of mean-daily

[3]Any analysis of pre- and post-Aspinall Unit impacts includes the cumulative impact of all reservoirs built before and after Blue Mesa Reservoir (Table A.5); however, Blue Mesa Reservoir clearly had the largest influence on river flows because of its large size.

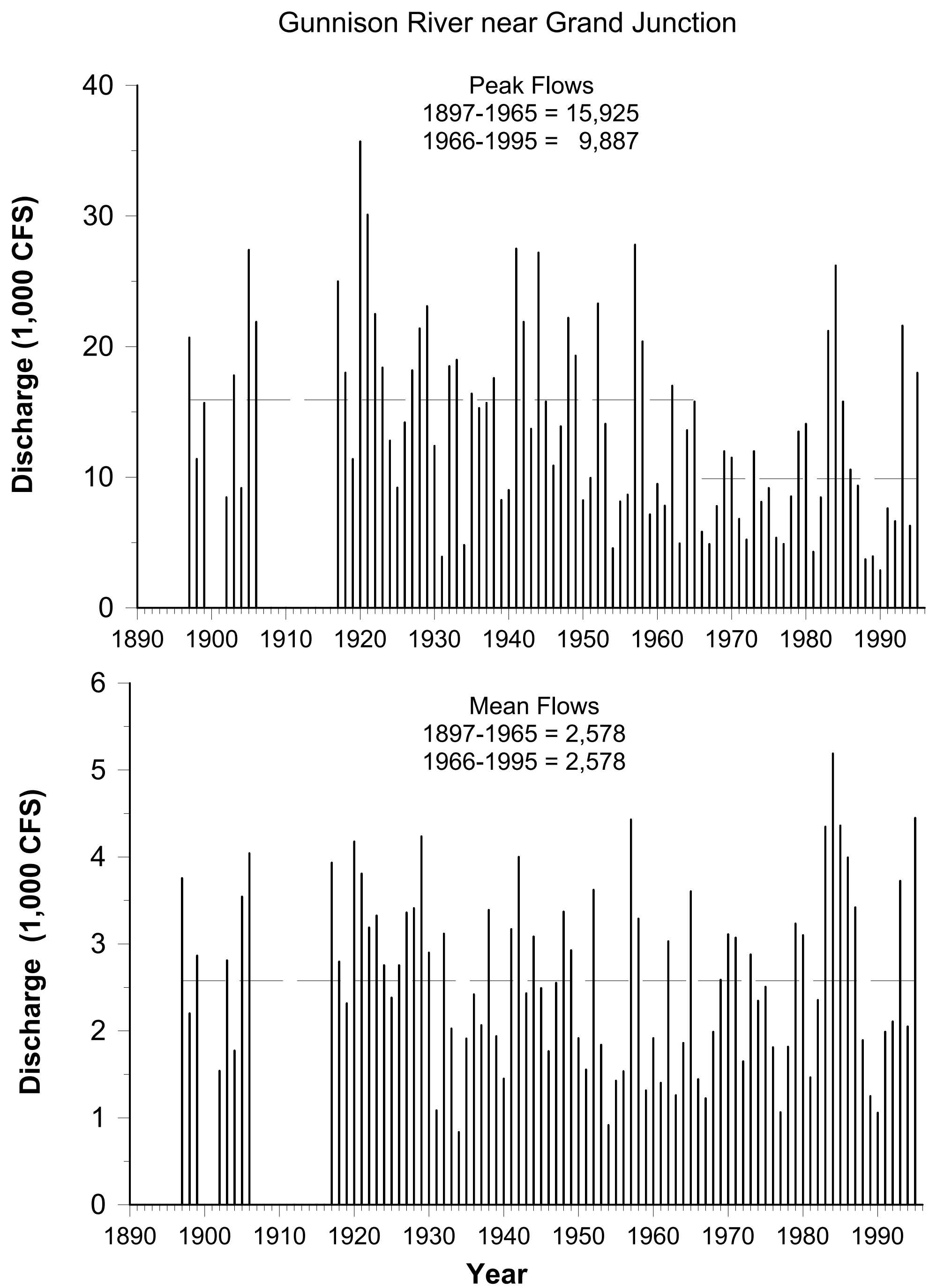
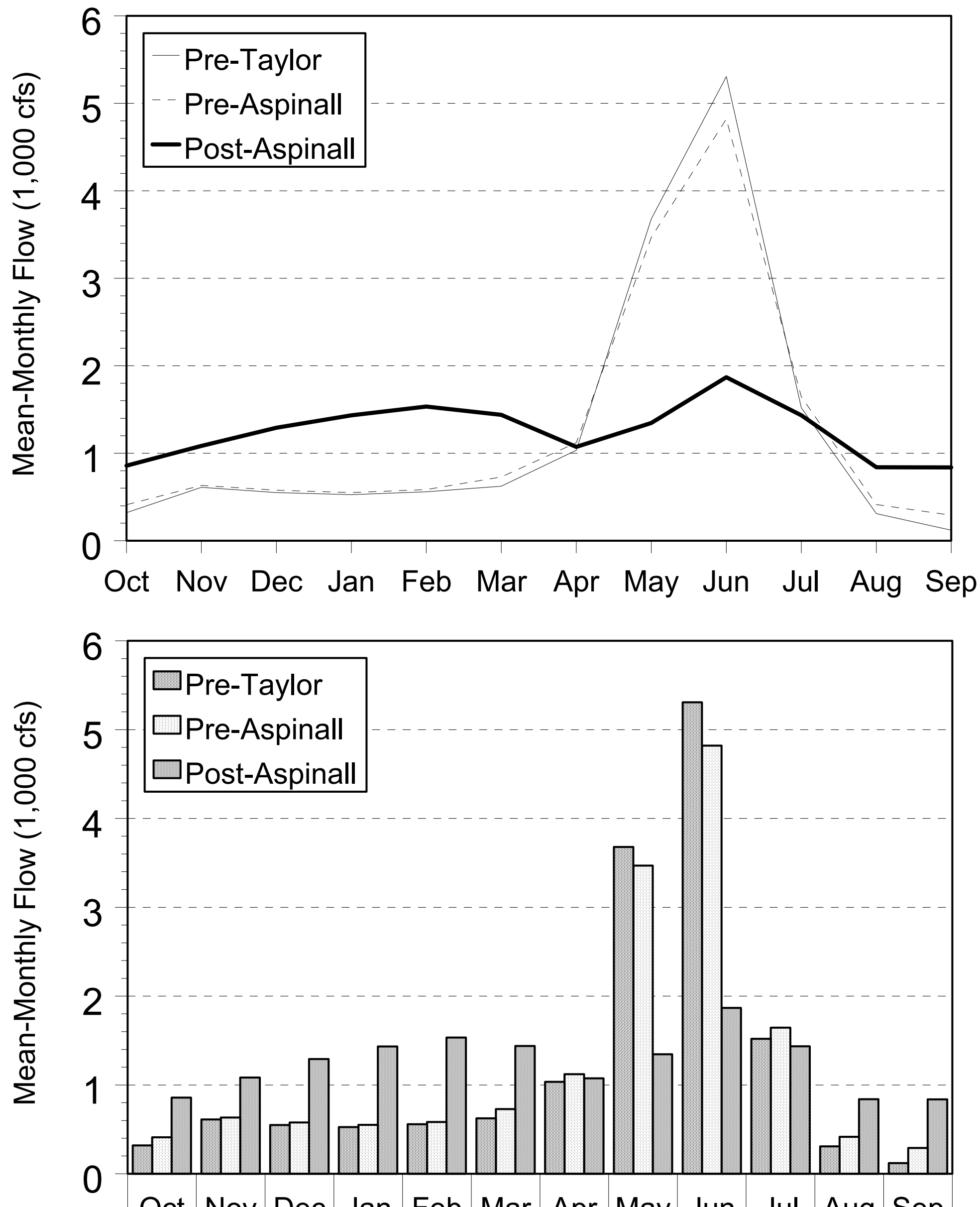


FIGURE 2.4. — Change in peak flow (highest mean-daily flow of the year; upper) and annual mean flow (lower) in the Gunnison River near Grand Junction (09152500) after construction of the Aspinall Unit. Figure 12 in Pitlick et al. (1999).

flows for all years in category) for both pre- and post-dam periods remained unchanged at 2,578 cfs (Pitlick et al. 1999; Figure 2.4). Pitlick et al. (1999) also compared streamflows in the East River, an unregulated tributary of the Gunnison River, for the same periods and found only a 3% decrease in mean peak flow between the same two time periods. Although there is evidence that the early part of the century was considerably wetter than the long-term average (e.g., Meko et al. 1991), the small decrease in mean peak flow in the East River and the unchanged mean annual flow in the Gunnison River suggest that climate change was only a small part of the observed decrease in peak runoff in the Gunnison River. See Pitlick et al. (1999) for more discussion on wet versus dry periods.

The pre-dam period used in Pitlick et al.'s (1999) analysis included water storage and irrigation diversions that occurred early in the century. Taylor Park Dam was constructed in 1937, and therefore peak river flows were altered at that time. Figure 2.5 shows the relative effects of Taylor Park Dam and the Aspinall Unit on year-round flows of the Gunnison River immediately downstream from the Aspinall Unit. The effects were modeled using existing data from the USGS gage below the Gunnison Tunnel to describe mean-monthly flows for 1971–1991 (USBR 1992). Pre-Taylor Park and pre-Aspinall Unit flows were then estimated by removing the influence of Taylor Park Reservoir and the Aspinall Unit to represent what flows would have been without these developments (USBR 1992). The resulting graphs show the classic effects of reservoir operation on river flow (Figure 2.5). Mean-monthly flow in June was reduced 9% after completion of Taylor Park Dam and then by an additional 56% by the Aspinall Unit. Mean-monthly flow in May was reduced by similar amounts (6 and 58%, respectively). Mean-monthly flows for the transition months of April and July were changed the least after reservoir construction — April flows increased about 4% and July flows decreased about 6% from Pre-Taylor Park to Post-Aspinall Unit. Mean-monthly flow increased in the remaining months, with the largest increases occurring in the normally low-flow winter months (December–March; range, 131–174% increase). A thorough analysis of impacts to the Gunnison River from operation of the Aspinall Unit and operation of the Gunnison Tunnel was provided by Diaz et al. (1996).

The above summary describes average conditions for the three different development periods; however, river flows are rarely average and can exhibit wide ranges depending upon the amount of moisture that accumulates in the mountains during winter and early spring and rate of snowmelt. Also, the early part of the 20th Century is considered to have been exceptionally wet (e.g., Meko et al. 1991), although not all rivers within the subbasin showed significant differences in maximum flows during snowmelt runoff (Pitlick et al. 1999). Exceedance probabilities for unregulated April–July inflow to Blue Mesa Reservoir and to the Gunnison River at the USGS gage near Grand Junction for 1937–1997 are illustrated in Figure 2.6. The early part of the century was excluded from these analyses to correspond to construction of Taylor Park Reservoir and to ensure that the curves represent recent conditions. Unregulated inflow ranged from 0.167 to 1.434 maf for Blue Mesa Reservoir and from 0.281 to 3.147 maf for the Gunnison River near Grand Junction during that period. Volumes that were equaled or exceeded 20, 40, 60 and 80% of the time were 0.974, 0.790,



	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Pre-Taylor	0.32	0.611	0.55	0.526	0.559	0.624	1.035	3.679	5.307	1.519	0.309	0.121
Pre-Aspinall	0.411	0.633	0.578	0.551	0.584	0.729	1.12	3.469	4.821	1.645	0.415	0.292
Post-Aspinall	0.858	1.083	1.291	1.433	1.534	1.439	1.074	1.346	1.868	1.434	0.84	0.838

Months of the Year

FIGURE 2.5. — Effect of the Aspinall Unit on mean-monthly flows of the Gunnison River below the Gunnison Tunnel (09128000). Post-Aspinall Unit flows were developed from gage readings during 1971–1991. Pre-Taylor Park and pre-Aspinall Unit flows were estimated by removing the influence of Taylor Park Reservoir and the Aspinall Unit to represent what flows would have been without these developments.

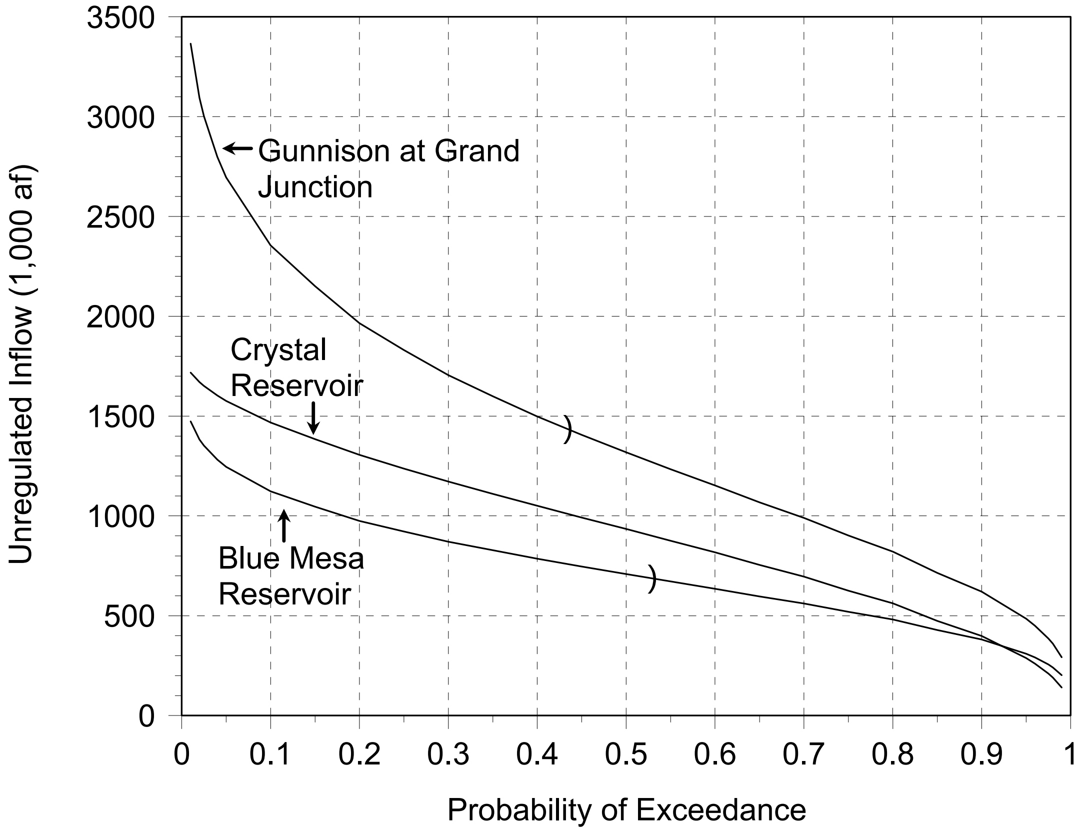


FIGURE 2.6. — Probability of different levels of unregulated April–July inflow to Blue Mesa Reservoir (bottom line), Crystal Reservoir (i.e., the entire Aspinall Unit, middle line), and to the Gunnison River near Grand Junction (09152500; upper line) based on the historical record (Blue Mesa Reservoir and the Gunnison River near Grand Junction, 1937–1997; Crystal Reservoir, 1977–1997). Closed circles (●) represent means for 1961–1990, which is used by NRCS to compare predicted unregulated inflow for April–July every spring — Blue Mesa Reservoir, 698,000 af and Gunnison near Grand Junction, 1,448,000 af (not calculated for Crystal Reservoir because of the shorter period of record).

0.640 and 0.483 maf for Blue Mesa Reservoir and 1.965, 1.507, 1.160, and 0.824 maf for the Gunnison River near Grand Junction (Table A.9). There was no significant difference between pre- (1937–1965) and post-Aspinall Unit (1966–1997) periods for either location (*t*-Test, *P*>0.1). NRCS compares average inflow for 1961–1990 with the current year's predicted volume when runoff forecasts are made. These averages are 0.698 maf for Blue Mesa Reservoir and 1.448 maf for the Gunnison River near Grand Junction.

Figures 2.7 and 2.8 show relationships between unregulated inflow and peak flow for the two sites discussed above for the pre- and post-Aspinall Unit development periods. Peak flows have declined dramatically in years with similar volumes of unregulated inflow. Based on regression lines, peak flows for similar volumes of inflow have declined 46–73% in the Gunnison River downstream from the Aspinall Unit (Figure 2.7) and 35–81 % in the Gunnison River near Grand Junction (Figure 2.8). Changes in the Gunnison River near Grand Junction are affected by other reservoirs in addition to the Aspinall Unit. Although, differences in flow as measured in cfs are greatest in years with highest inflow, decreases measured as percent change are greatest in years with lowest inflow. Change in frequency of occurrence for Gunnison River flows (USGS gage near Grand Junction) for the three development periods is presented in Figure A.1. Values of $Q_{1.5}$ were 13,900 cfs before Taylor Park Reservoir, 10,800 between construction of Taylor Park and Blue Mesa reservoirs, and 6,750 after construction of Blue Mesa Reservoir (Table A.6).

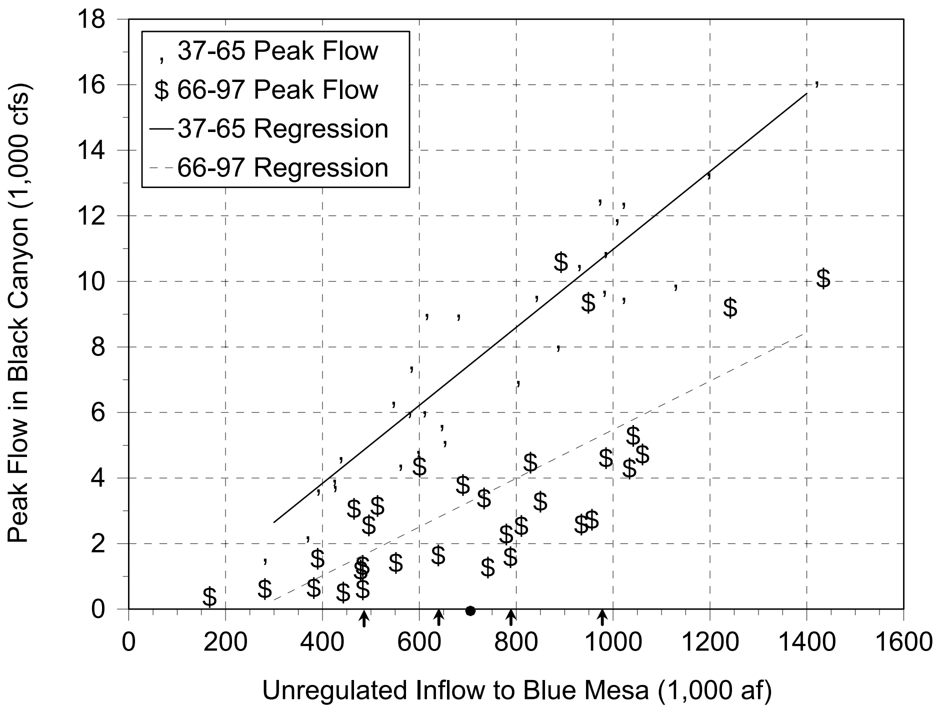


FIGURE 2.7. — Relationship of peak river flow (highest mean-daily flow of the year) downstream from Gunnison Tunnel to unregulated April–July inflow to Blue Mesa Reservoir for two water-development periods — pre Aspinall Unit, 1937–1965 and post Aspinall Unit, 1966–1997. Arrows along the x axis represent volumes that were equaled or exceeded 80, 60, 40, and 20% of the time during 1937–1997 (483,000, 640,000, 790,000, and 974,000 af [Table A.9]); closed circle represents the mean for 1961–1990, 698,000 af). Both regression lines were significant (*P*<0.001; 1937–1965, R^2=0.87 and 1966–1992, R^2=0.56) and significantly different from each other (ANCOVA, *P*<0.001).

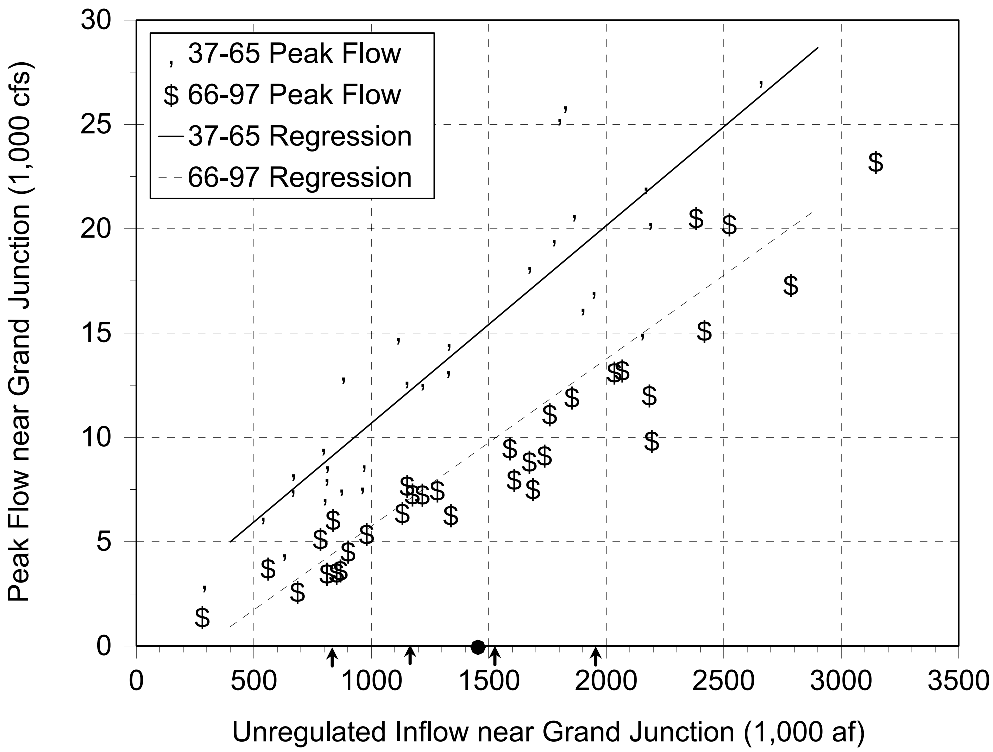


FIGURE 2.8. — Relationship of peak flow (highest mean-daily flow of the year) in the Gunnison River near Grand Junction (09152500) to unregulated April–July inflow to the same location for two water-development periods — pre Aspinall Unit, 1937–1965 and post Aspinall Unit, 1966–1997. Arrows along the x axis represent volumes that were equaled or exceeded 80, 60, 40, and 20% of the time during 1937–1997 (824,000, 1,160,000, 1,507,000, and 1,965,000 af [Table A.9]); closed circle represents the mean for 1961–1990, 1,448,000 af). Regression lines were significant (*P*<0.001; 1937–1965, R^2=0.82 and 1966–1992, R^2=0.89) and significantly different from each other (ANCOVA, *P*<0.001).

As with the Colorado River, base flows are locally impacted by water diversions for irrigation of agricultural lands during the growing season. Two major diversion structures are located within endangered-fish habitat in the Gunnison River — Hartland Diversion near Delta and Redlands Diversion, about 2.5 mi upstream from its mouth. Redlands Water and Power Company holds a senior water right on the Gunnison River and can divert all the water in the river under certain conditions; this dewaters a 2.5-mi reach of the lower Gunnison River. Most (≈90%) of the diverted water enters the Colorado River about 5 mi downstream from the mouth of the Gunnison River after being used to generate power. As with the structures on the Colorado River, Hartland and Redlands dams are barriers to fish movement. A fishway was recently built around Redlands Dam (Section 3.2.1) and the Recovery Program is considering options to restore passage at Hartland Dam.

A minimum flow of 300 cfs has been recommended for the river downstream from Redlands Dam (measured at State of Colorado gage GUNREDCO; Burdick 1997). This recommendation is primarily to provide access to the fishway for migrating Colorado pikeminnow during low water periods, but it also provides some year-round habitat for resident fish in this short reach of critical habitat. However, this flow does not provide optimum year-round habitat. Table 2.1 summarizes the frequency that a minimum of 300 cfs was met in this reach both before and after construction of Blue Mesa Reservoir based on USGS records from the Grand Junction gage. Releases from the reservoir increased the frequency that flows of 300 cfs or higher occurred downstream from the diversion, especially in winter. However, flows of at least 300 cfs would have occurred in this reach almost all of the time (>99%) if Redlands Diversion did not exist (Table 2.1). Even before construction of Blue Mesa Reservoir, flows of less than 300 cfs would have occurred for a combined total of only 256 d in the period of record (56 yr) if the water had not been diverted from the river. The longest consecutive period would have been l39 d in 1934, which included

TABLE 2.1. — Percentage of the time, by month, that mean-daily river flows met or exceeded 300 cfs downstream from Redlands Diversion Dam during two water-development periods — before construction of Blue Mesa Reservoir (1897–1899, 1902–1906, and 1917–1965) and after construction of Blue Mesa Reservoir (1966–1997).

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Before Construction of Blue Mesa Reservoir[a]											
12.2	19.6	43.4	85.4	99.8	95.7	70.9	42.2	32.1	48.7	63.9	29.1
After Construction of Blue Mesa Reservoir[a]											
78.6	79.5	81.7	89.9	95.5	93.1	69.8	64.6	84.6	88.0	82.7	83.7
Before Construction of Blue Mesa Reservoir, Assuming Redlands Diversion Did Not Exist[b]											
100.0	100.0	100.0	99.9	100.0	98.9	96.8	94.7	96.2	98.8	99.8	100.0
After Construction of Blue Mesa Reservoir, Assuming Redlands Diversion Did Not Exist[b]											
100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

[a] Values were calculated based on a flow of at least 1,050 cfs at the USGS gage near Grand Junction (09152500) and assuming a diversion of 750 cfs at the Redlands Dam.

[b] Values were calculated based on a flow of at least 300 cfs at the USGS gage near Grand Junction (09152500) and assuming no diversions at the Redlands Dam.

mid June through the end of October. The second longest period (66 d) was in 1931. Four of the 10 yr when these low flows occurred were in drought years of the 1930s. An interim agreement between the Service, Reclamation, and the Colorado Water Conservation Board (CWCB) provides for releases of stored water from the Aspinall Unit to meet a 300 cfs minimum flow in certain months during all but the driest years (USBR and USFWS 1995). Meeting the 300 cfs minimum flow downstream from Redlands Dam during the migration period will continue to be one component of flow recommendations for the Gunnison River.

McAda and Fenton (1998) mapped surface area of habitat in the Gunnison River at flows ranging from 981 to 15,800 cfs (referenced to USGS gage 09152500). They found that pools and slow runs were maximized at 981 cfs, the lowest flow they measured. This level is consistent with flows (1,050 cfs) that occur in the Gunnison River when a minimum of 300 cfs is provided below Redlands Dam (Redlands senior water right is 750 cfs). Pools and slow runs are preferred habitats for razorback sucker and Colorado pikeminnow (sections 3.2.2 and 3.3.2), which suggests that ~1,000 cfs approximates a base flow that will provide suitable habitat during summer, autumn, and winter. Although lower flows were not measured, McAda and Fenton (1998) believed that 750 cfs would probably provide adequate habitat under extremely dry conditions.

2.1.3 Historical Operation of the Aspinall Unit

Operation of Blue Mesa Reservoir has generally been to maximize water storage and meet other CRSP purposes. The historical objective of Aspinall Unit operation was to fill Blue Mesa Reservoir (elevation 7,519.4 ft, 940,700 af) in late June or early July and then to gradually reduce volume to a target elevation of 7,490 ft (580,000 af) by December 31. The December target was selected to reduce icing damage to property and roads along the Gunnison River upstream of Blue Mesa Reservoir. Releases are based upon downstream water needs, reservoir volume and projected unregulated inflow to the Aspinall Unit. Reservoir operations in winter and early spring are based upon predicted unregulated inflow to the reservoir from water stored in the Gunnison basin's snowpack. Releases are increased when high inflow is predicted and reduced when low inflow is predicted. Projected spring and early summer releases are refined as forecasts of unregulated inflow to the reservoir are updated by NRCS and adjusted as forecasts or actual runoff changes. August through December releases are designed to meet downstream water needs and to lower reservoir storage to the winter target. Cessation of irrigation diversions at the Gunnison Tunnel and the need to reduce water volume to the winter target often resulted in increasing flows in late autumn and winter.

Historical reservoir operations during spring required calculating the amount of water to be released downstream during the period between the latest forecast and July and distributing releases over the remaining months considering power plant capacity and Gunnison Tunnel demands. Morrow Point and Crystal reservoirs are smaller than Blue Mesa Reservoir (Table A.8) and their content does not generally affect projected releases from Blue Mesa Reservoir and the Aspinall Unit as a whole. They are used primarily for power generation, including peaking power, and then reregulating the downstream releases to eliminate water fluctuations in the Gunnison River downstream from Crystal Dam. The exception is when unregulated tributary input to these small reservoirs is high, which may require reducing releases from Blue Mesa Reservoir to reduce the chance of spilling one or both of the smaller reservoirs or to protect downstream urban areas from flooding.

Since Crystal Reservoir was closed in 1976, releases have ranged from a low of 65 cfs in November 1981 to a high of 11,275 in June 1984. Equivalent flows downstream from Gunnison Tunnel were 65 and 10,600 cfs (compared to extremes of 0 and 18,600 cfs prior to construction of Blue Mesa Reservoir, but after construction of the Gunnison Tunnel). Since 1985, Reclamation has maintained a minimum flow of 300 cfs between the Gunnison Tunnel and the confluence with the Smith Fork River except during extreme drought. Based on recommendations from CDOW, changes in releases from Crystal Dam (both increases and decreases; ramping rate) are kept to 300–500 cfs/d (if possible) to minimize habitat changes that could negatively affect aquatic resources downstream from the Gunnison Tunnel. Autumn, winter, and spring flows are also adjusted, when possible, to avoid dewatering brown trout *Salmo trutta* redds deposited in autumn and rainbow trout *Oncorhynchus mykiss* redds produced in spring.

In 1993, Reclamation began meeting with public and private organizations that benefitted from or were otherwise interested in operation of the Aspinall Unit. Meetings were held three times a year (January, April, and August) to discuss and provide input to reservoir operations during the upcoming season based on projected inflow to Blue Mesa Reservoir. Initiation of the meetings coincided with the beginning of research to determine the effect of operation of the Aspinall Unit on endangered fishes, as well as efforts by the National Park Service (USNPS) to quantify reserved water rights for Black Canyon of the Gunnison National Park, immediately downstream from Crystal Reservoir. During this period, Reclamation, with input from the Service, USNPS, WAPA, CDOW, Colorado Water Resources Division, Gunnison basin water users and other interested parties (see Table A.10 for a list of organizations represented at the meetings), modified release patterns from the Aspinall Unit to mimic the shape of a natural hydrograph while continuing to meet other responsibilities of the project.

As described above, historical operation was to calculate the amount of water that would have to be released during the spring snowmelt period and distribute it evenly through spring and early summer months. During the research period, water that would have been bypassed around the power plant was reshaped to provide a maximum release from Crystal Reservoir of 4,000 cfs (2,000 cfs through the turbines and 2,000 cfs through the bypass tubes) for at least a short period each spring. The reshaping of the hydrograph occurred primarily in low to average water years when more of the inflow would have been stored and released more slowly under historical operations. Historical operation often resulted in releases of 4,000 cfs or greater during above-average years because there was insufficient storage to hold unregulated inflow to the Aspinall Unit under those conditions. Highest flows occurred when Blue Mesa releases in conjunction with tributary input to Morrow Point and Crystal reservoirs exceeded their small storage capacity which forced water over the spillway at Crystal Reservoir.

2.1.4 Aspinall Unit Operation During the Study Period

Table 2.2 and Figure 2.9 describe Aspinall Unit releases for the study period. More detailed descriptions of unregulated inflow to the Aspinall Unit, Blue Mesa volume and releases from Crystal Reservoir are provided in Tables A.11–A.24 and Figures A.2–A.8. During this period, 3 yr (1992, 1994, and 1998) were dryer than the long-term average and 4 yr (1993, 1995, 1996, and 1997) were wetter than the long-term average. Releases of 4,000 cfs or greater were made from Crystal Reservoir for all years of the study, but duration of releases and maximum releases from the reservoir varied greatly (Table 2.2). During dryer than average years, flows of 4,000 cfs or greater were maintained for only 2 d with ramping up and down from the maximum power generation flow of 2,000 cfs varying between 14 and 31 d, depending on water availability. Using a ramping rate of 300 cfs/d, ramping from 2,000 to 4,000 cfs and back down again requires a minimum of 14 d. During wetter years, flows equaling or exceeding 4,000 cfs were released from Crystal Reservoir for 30 d in 1996, 32 d in 1993, 48 d in 1997, and 101 d in 1995.

TABLE 2.2. — Summary of unregulated inflow to the Aspinall Unit and release patterns from Crystal Reservoir during the study period.

Year	Aspinall Inflow, April–July		Maximum Crystal Release (cfs)	Number of days from February to September that mean-daily Crystal releases exceeded:			
	Total (maf)	Percent of Average[a]		2,000 cfs	3,000 cfs	4,000 cfs	5,000 cfs
1992	0.608	67	4,036	12	7	1	0
1993	1.266	140	5,444	212	77	32	8
1994	0.620	69	4,140	31	8	2	0
1995	1.607	178	10,337	164	114	101	74
1996	1.033	115	5,705	94	48	30	9
1997	1.300	144	5,394	179	88	48	8
1998	0.706	78	4,012	14	8	2	0

[a] Based on the 30-yr average for 1961–1990 of 902,000 af.

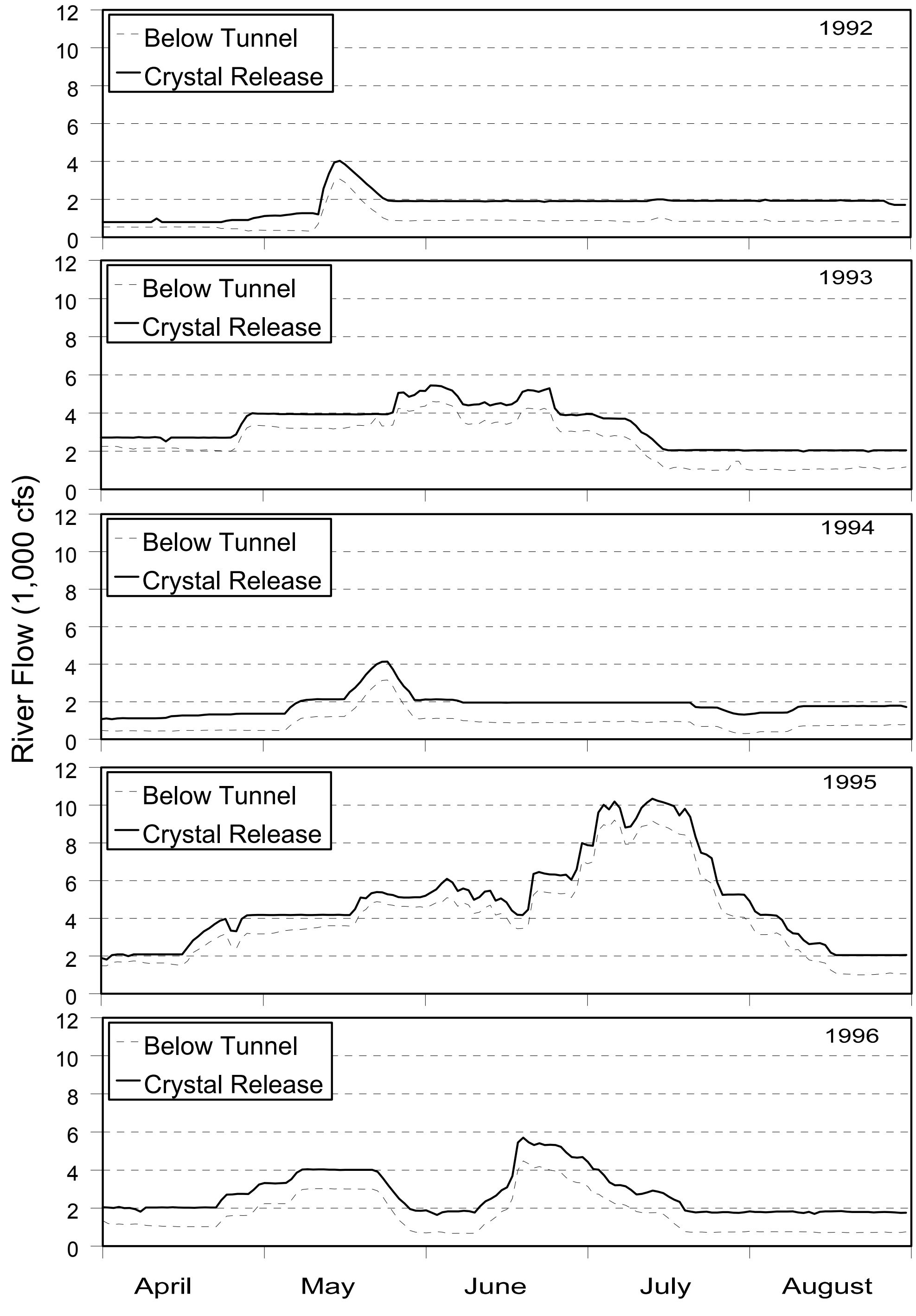


FIGURE 2.9. — Mean-daily river flow of the Gunnison River downstream from Crystal Reservoir during April–August, 1992–1998. The difference between the two values reflects diversions through the Gunnison Tunnel.

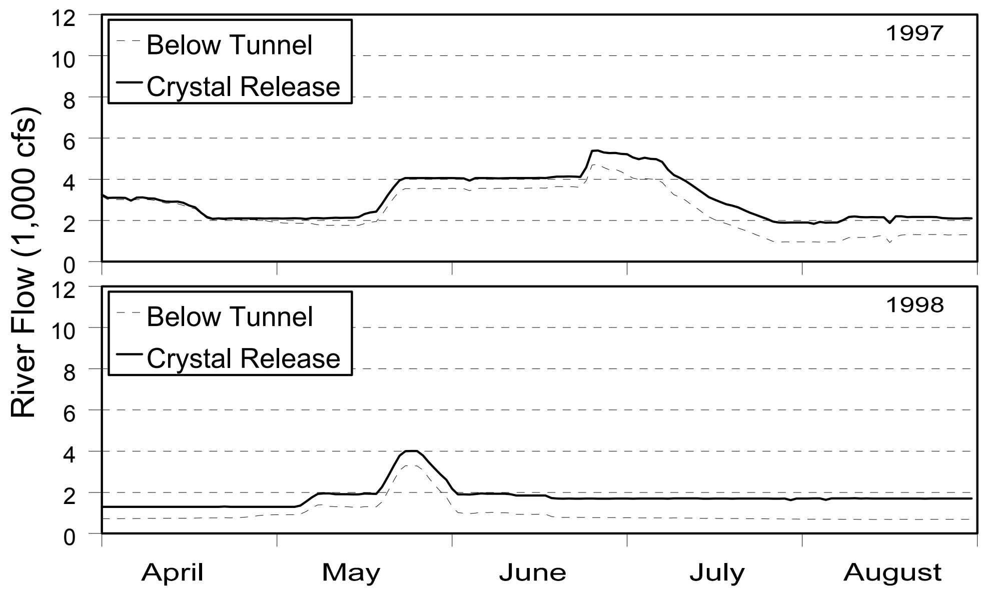


FIGURE 2.9. — Continued.

The spring peaks created during the dryer-than-average years of 1992, 1994, and 1998 were clearly artificially generated peaks because storage capacity was adequate to temporarily store runoff and release the water over a longer period of time. Reservoir releases resulted in a double peak in 1996 because after generating an artificial peak in May and dropping back to maximum power-generation release of 2,000 cfs, inflow increased above the forecasted volume and water needed to be released because of insufficient storage capability. Releases during 1993, 1995, and 1997 were dictated by the large volume of water entering the three reservoirs and peak releases from Crystal were probably about the same as they would have been with similar water volumes under historical operating rules. The highest spring release occurred in 1995, which resulted from a high snowpack and much wetter spring than average (May precipitation was 300% of average). However, the peak was not reached until mid July, much later than the historical average (late May). Reasons for the late peak were (1) the cool, wet spring meant that much of the inflow to the Aspinall Unit came late in the year, and (2) Reclamation reduced releases from Blue Mesa while snowmelt runoff was at its peak in downstream tributaries to prevent flooding in and around the town of Delta.

Table 2.3 and Figure 2.10 show the relationship of flows downstream from Crystal Reservoir to Gunnison River flows near Delta and near Grand Junction. Timing of Gunnison River peaks corresponded well with Crystal releases because outflow from the reservoir was often a major portion of peak flow. Peak flow in the entire Gunnison River was most affected by modified operations at the Aspinall Unit in 1992 and 1994 when flows downstream from the Gunnison Tunnel were 63% and 50% of the spring peaks recorded at the lowermost gage on the Gunnison River. In contrast, Aspinall Unit releases composed the smallest percentage of spring peaks in the mainstem Gunnison River during the high-water years of 1993 (15%) and 1995 (18%). The Gunnison River reached its highest mean-daily peak flow

TABLE 2.3. — Mean-daily flow (cfs) of the Gunnison River on the highest day of the year at four gaging stations — Crystal Reservoir, Gunnison River below Gunnison Tunnel (09128000), Gunnison River near Delta (09144250), and Gunnison River near Grand Junction (09152500).

	Crystal Release/Below Tunnel			Gunnison River near Delta		Gunnison River near Grand Junction	
Year	Crystal Release	Below Tunnel	Date	Flow	Date	Flow	Date
1992	4,036	3,070	5/15	4,420	5/15	6,360	5/28
1993	5,444	4,620	6/02	15,400	5/17	20,500	5/18
1994	4,140	3,160	5/24	5,000	5/23	6,040	5/23
1995	10,337	9,160	7/13	12,800	6/06	17,300	6/18
1996	5,705	4,480	6/19	7,110	5/17	7,670	5/18
1997	5,394	4,730	6/26	9,720	6/09	12,000	5/26
1998	4,012	3,290	5/25	7,880	5/22	9,360	5/22

in 1993, (20,500 vs 17,300 cfs in 1995; Table 2.3) but produced the greatest volume of runoff in 1995 (Table 2.2). In both 1993 and 1995, Aspinall Unit releases were held at 5,000 cfs or less during the peak of runoff in downstream tributaries to prevent flooding near Delta. However, unexpectedly high inflow to Blue Mesa Reservoir in 1995 forced a late release that increased to 10,000 cfs, which extended runoff in the mainstem Gunnison River and produced a second peak that was almost as high as the first. Because runoff in the downstream tributaries had subsided by that time, Aspinall Unit releases were 56% of the second peak. The late release from the Aspinall Unit extended runoff longer than normal and base flows were not reached until mid August in 1995. In most years, including the high flow year of 1993, base flows are reached by mid July. Late releases also generated a second peak in 1996 when inflow to the Aspinal Unit increased unexpectedly in mid June. Although Aspinall Unit releases were 42% of the first peak in the mainstem river which occurred in mid May, the late releases contributed 74% of the total water volume. Peak Aspinall Unit releases in both 1997 and 1998 were about one-third of the highest mean-daily river flow recorded at the USGS gage near Grand Junction.

Colorado River flows during the study period are presented in Figure 2.11. The Colorado River at the Colorado-Utah state line peaked at 15,800 cfs in 1992, 44,000 cfs in 1993, 13,100 cfs in 1994, 48,100 cfs in 1995, 28,500 cfs in 1996, 36,000 cfs in 1997, and 24,700 cfs in 1998. During this period, the Gunnison River contributed an average of 34% of peak flows in

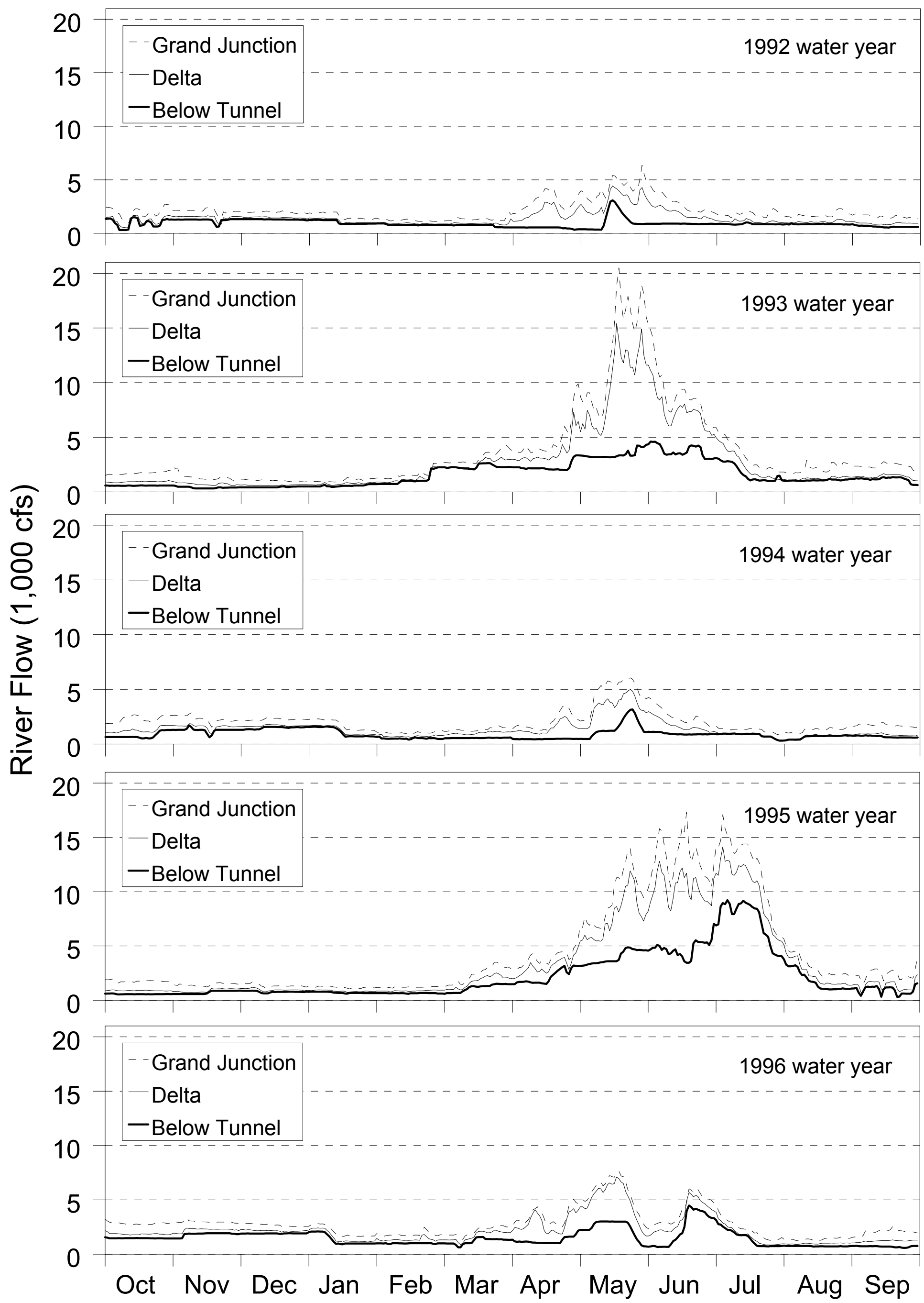


FIGURE 2.10. — Mean-daily river flow of the Gunnison River at three USGS gaging stations (near Grand Junction [09152500], at Delta [09144250], and below Gunnison Tunnel [09128000]), 1992–1998. Flows below the tunnel reflect water released from Crystal Reservoir with 400–1,200 cfs diverted through the Gunnison Tunnel (owned by Uncompahgre Water Users) during the irrigation season, April–October.

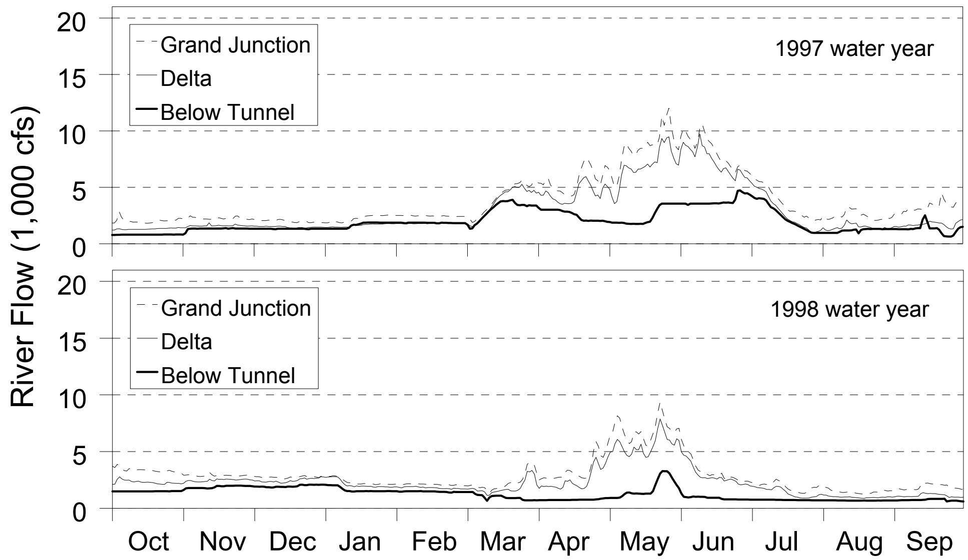


FIGURE 2.10. — Continued.

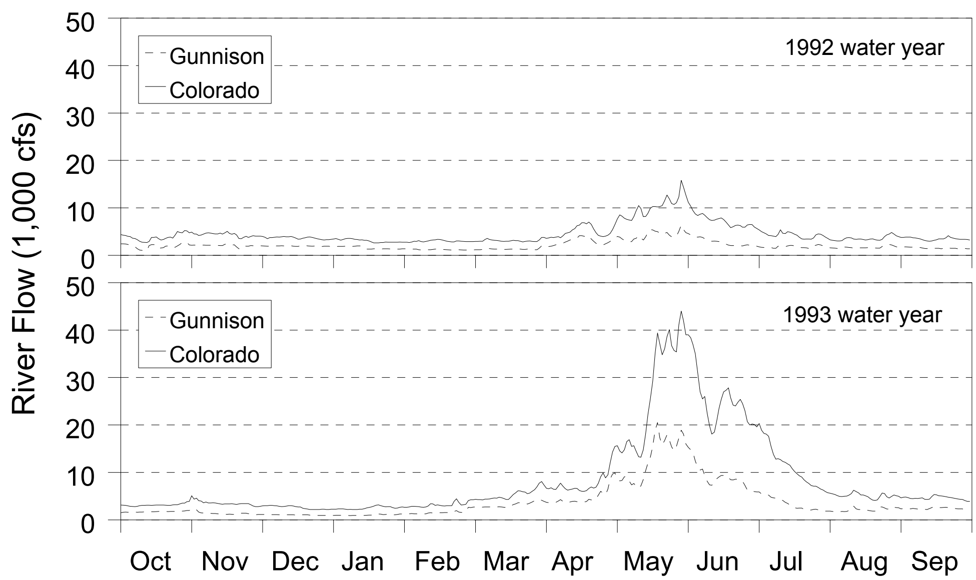


FIGURE 2.11. — Mean-daily river flow of the Colorado River at the USGS gaging station at the Colorado-Utah state line (09163500) and the Gunnison River at the USGS gaging station near Grand Junction (09152500), 1992–1998.

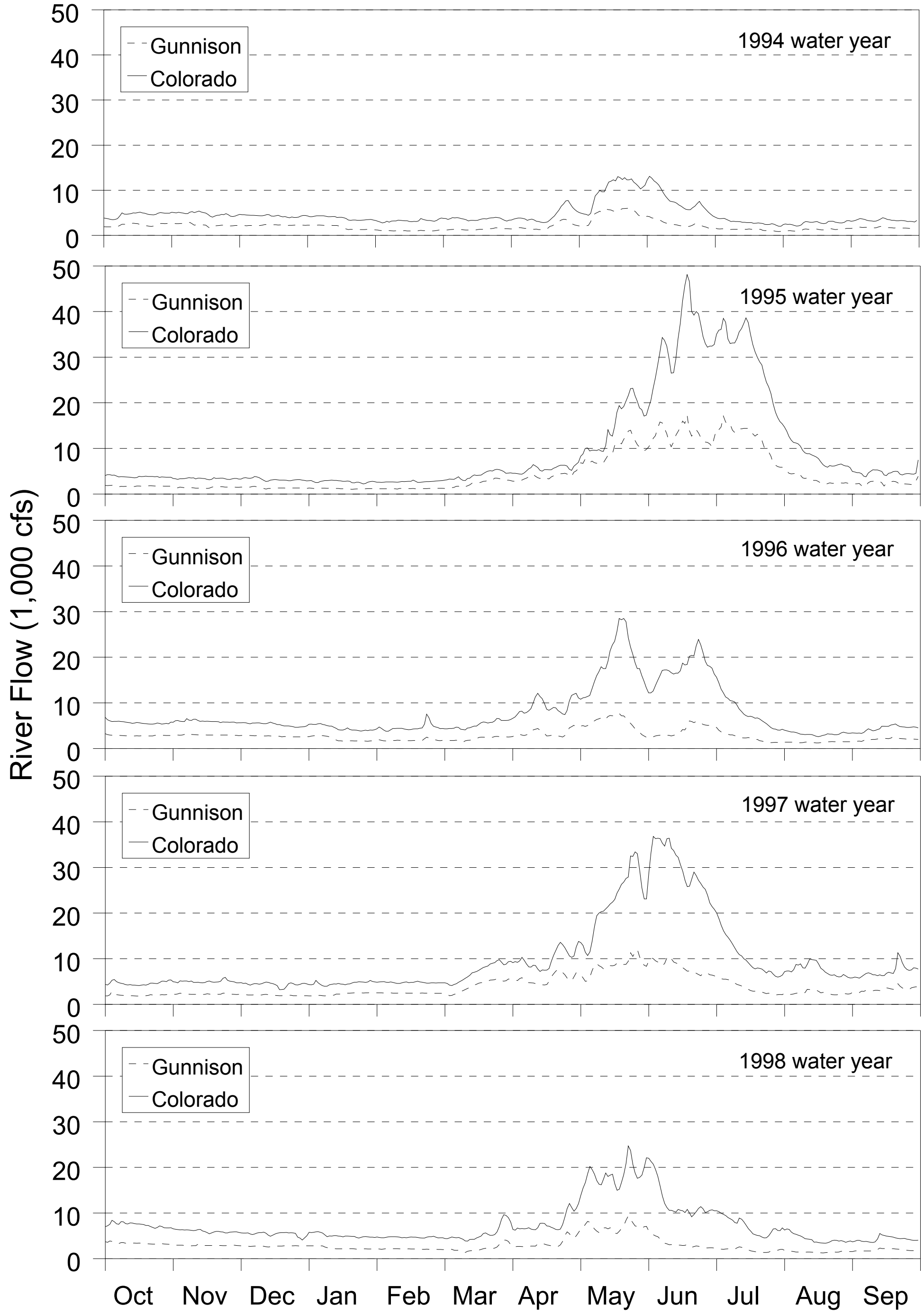


FIGURE 2.11. — Continued.

the Colorado River at the Colorado-Utah state line (1992, 42%; 1993, 43%; 1994, 32%; 1995, 36%; 1996, 25%; 1997, 27%; 1998, 34%). There was no difference between wet (mean, 34%) and dry (33%) years.

2.2 GEOMORPHOLOGY

2.2.1. Longitudinal Variation

The Gunnison and Colorado rivers are alluvial, gravel-bed rivers through most of the reaches occupied by endangered fishes (Pitlick et al. 1999). However, the Colorado River becomes primarily sand bed in the 65 mi upstream from its confluence with the Green River (Pitlick and Cress 2000). Pitlick and Cress (2000) provided descriptions of longitudinal changes in geomorphology of the Colorado River, which are summarized below.

Upstream from the Grand Valley (within historical habitat of Colorado pikeminnow and razorback sucker, but upstream of their current distribution in the Colorado River because dams prevent upstream movement; Chapter 3), the Colorado River flows across a wide alluvial valley with some agricultural activity and then enters DeBeque Canyon, which restricts the lateral movement of the river. Within DeBeque Canyon, the river is constrained further by diking along the railroad on the west side of the river and along Interstate 70 on the east side. River slope averages 10.4 ft/mi within the alluvial valley and 7.9 ft/mi within DeBeque Canyon (Pitlick and Cress 2000; Figure 2.12; Table 2.4).

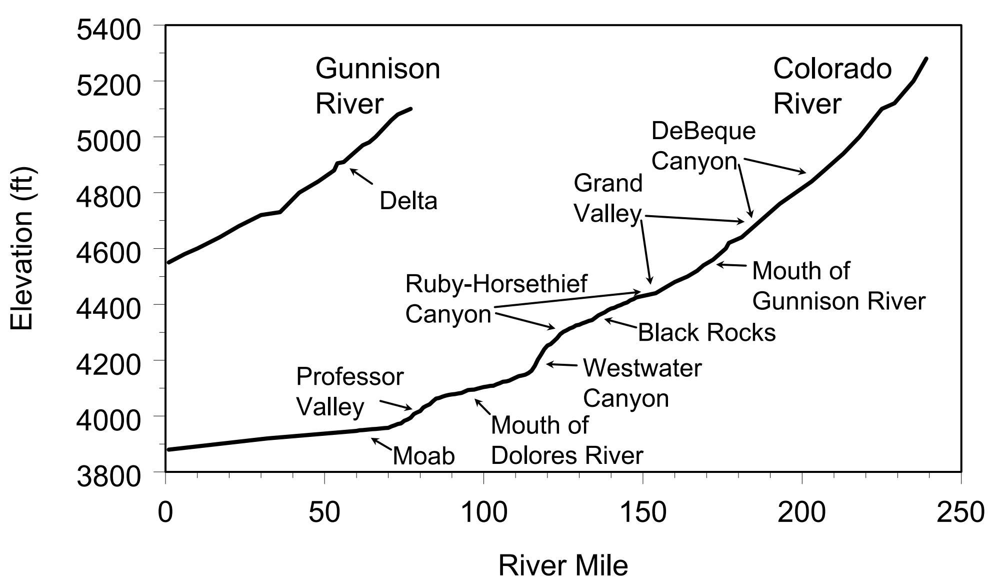


FIGURE 2.12. — Longitudinal profile of the Gunnison and Colorado rivers. River mile 0 for the Gunnison River is its confluence with the Colorado River. River mile 0 for the Colorado River is its confluence with the Green River.

TABLE 2.4. — Average slope, bankfull width, depth, and median surface grain size (D_{50}) of the Colorado River in specific subreaches. Excerpted from Table 1 in Pitlick and Cress (2000).

Reach Description and Location	Slope (ft/mi)	Width (ft)	Depth (ft)	D_{50} (in)
Rulison-DeBeque (RM 228–205)	10.4	374	8.0	2.244
DeBeque Canyon (RM 204–198)	7.9	253	10.2	2.047
15-mile reach (RM 186–172)	9.2	440	8.3	2.283
18-mile reach (RM 171–154)	6.9	574	9.9	2.047
Ruby-Horsethief Canyon (RM 153–129)	5.3	423	11.9	1.850
Cisco-Fish Ford (RM 113–96)	3.5	482	14.7	1.496
Dewey (RM 94–88)	2.5	433	16.9	1.338
Professor Valley (RM 86–79)	7.9	666	15.1	2.756
Big Bend (RM 78–71)	5.2	348	21.1	2.480
Moab (RM 69–66)	1.8	495	16.8	1.102
Potash (RM 64–48)	1.5	646	14.8	0.001

After leaving DeBeque Canyon, the Colorado River enters the Grand Valley and meanders through a broad agricultural and residential valley with alternating single-thread and multi-thread reaches (Pitlick et al. 1999). These multi-thread reaches contain more diverse and heterogeneous habitats than other river sections — side channels and backwaters are common. The natural meandering of the channel is restricted in some areas by riprap and construction of levees; however, most of the channel is unconstrained and free to move within the floodplain (Pitlick and Cress 2000). Substrates are primarily gravel-cobble-rubble. The Grand Valley contains most of the floodable bottomlands found in the Colorado River (Irving and Burdick 1995). Average slope of the Colorado River is 9.2 ft/mi upstream from its confluence with the Gunnison River (15-mile reach) and 6.9 ft/mi downstream from the confluence (18-mile reach; Pitlick and Cress 2000; Figure 2.12). Flooded bottomlands and the heterogeneous mix of habitats found in multi-thread reaches provide important habitats for razorback sucker and Colorado pikeminnow (Sections 3.2.2 and 3.3.2).

Downstream from the Grand Valley in Ruby-Horsethief Canyon, the channel is more incised with fewer side channels, but maintains a predominantly gravel-cobble substrate except for a 1-mi-long bedrock reach known as Black Rocks. The channel is more constrained than in the upper river, but a small floodplain is present along most of the reach (Pitlick and Cress 2000). Black Rocks is formed by upthrust black metamorphic gneiss that resists erosion and the reach is much deeper than up- and downstream reaches. Maximum water depth is 50 ft along the sheer walls formed by the metamorphic rock (Valdez and Clemmer 1982). Mean slope in Ruby-Horsethief Canyon is 5.3 ft/mi (Pitlick and Cress 2000). After leaving Black Rocks, the river becomes relatively shallow again until it enters Westwater Canyon about 11 mi downstream. The metamorphic rocks reemerge in Westwater Canyon and form a narrow canyon with a deep channel (maximum of 70 ft, Chart and Lentsch1999a) and a series of rapids, strong eddies, and strong currents. The river drops an average of 11.8 ft/mi in the 14-mi-long canyon (Figure 2.12), but most of the change occurs in the short rapids in the upper half of the canyon. Black Rocks and Westwater Canyon provide important habitat for humpback chub (Section 3.4.1).

After leaving Westwater Canyon, river gradient decreases and sand and silt substrates become more prevalent, although larger substrates still dominate the channel. The river has a broad floodplain downstream from Westwater Canyon, but becomes more constrained after it passes the mouth of the Dolores River. It flows through relatively narrow canyons with another short section of minor rapids (Professor Valley, slope 7.9 ft/mi). Near Moab, Utah (about 46 mi downstream from Westwater Canyon), gradient decreases sharply (slope 1.8 ft/mi) and the Colorado River changes abruptly from predominately gravel to sand substrate (Pitlick and Cress 2000). An area of floodable bottomland occurs near Moab (Scott Matheson Wetland Preserve [WP]; Irving and Burdick 1995). The section between Moab and the mouth of the Green River has the lowest gradient of any reach of the Colorado River upstream of Lake Powell (slope 1.5 ft/mi; Pitlick and Cress 2000; Figure 2.12, Table 2.4). Shortly after meeting the Green River, the Colorado River enters Cataract Canyon — an 11-mi-long section of steep gradient and turbulent rapids — and then abruptly enters Lake Powell.

Overall, bankfull width and bankfull depth in the Colorado River increase systematically from up- to downstream reaches (Pitlick and Cress 2000). Average bankfull width increases from 374 ft in the upper river to 495 ft in the river just upstream from Moab and average bankfull depth increases from 8.2 to 16.7 ft in the same manner (Pitlick and Cress 2000). With the exception of the river downstream from Moab, bankfull depth increases downstream at about twice the rate of bankfull width. Downstream from Moab, the sand bed apparently makes it easier for the river to erode its banks, creating a channel with a higher width-to-depth ratio (Pitlick and Cress 2000). In contrast with average channel width and depth, average substrate size decreases from up- to downstream reaches (Pitlick and Cress 2000).

The Gunnison River is similar to the Colorado River upstream from Westwater Canyon, except that the channel is more incised and less complex. It has considerably fewer side channels and backwaters than the Colorado River within the Grand Valley. The most complex (i.e., multi-thread channels with a heterogenous mixture of in-channel habitats) section of the Gunnison River occurs at the upper end of critical habitat near Delta, where most floodable bottomlands occur (Irving and Burdick 1995; McAda and Fenton 1998). River gradient within critical habitat is lowest in the braided section near Delta (mean slope, 1.0 ft/mi; Pitlick et al. 1999), but it is relatively uniform downstream to its confluence with the Colorado River (range, 5.3–6.3 ft/mi; Figure 2.12).

Fish habitat along the Colorado and Gunnison rivers is largely controlled by the interaction of width, depth, slope, substrate size, and surrounding topography. Lamarra (1999) measured surface area of 37 macrohabitat types composing 8 major categories in 11 strata in the Colorado River and 1 stratum in the Gunnison River. Runs were the dominant habitat in all sections of the river composing 87.80% of total surface area. Riffles were next most-abundant (5.11%) followed by low-velocity habitats (3.67%), backwaters (1.56%), and slackwater (1.36%; see Lamarra [1999] for habitat definitions). Although runs dominated the entire river, the remaining habitats were distributed differently between up- and downstream reaches. Riffles and other fast-water habitats were most common in upper reaches, whereas low-velocity habitats were most common in downstream reaches (Lamarra 1999). Backwaters were found throughout the river, but were a larger proportion of total surface area in the upper Colorado River than in the lower river. Proportion of macrohabitats in the Gunnison River stratum was comparable to the Colorado River upstream from Westwater Canyon.

McAda (1993) averaged surface area of backwaters for a 3-yr period (1989–1991) in two reaches of the Colorado River that were sampled as part of autumn monitoring for YOY Colorado pikeminnow (Figure 2.13). Backwaters were larger and more common in the higher gradient, braided area of the river upstream from Westwater Canyon than in lower reaches of the river. However, there are important differences in backwater type between the two areas. Most backwaters in the upper Colorado River are side channels that are blocked at the

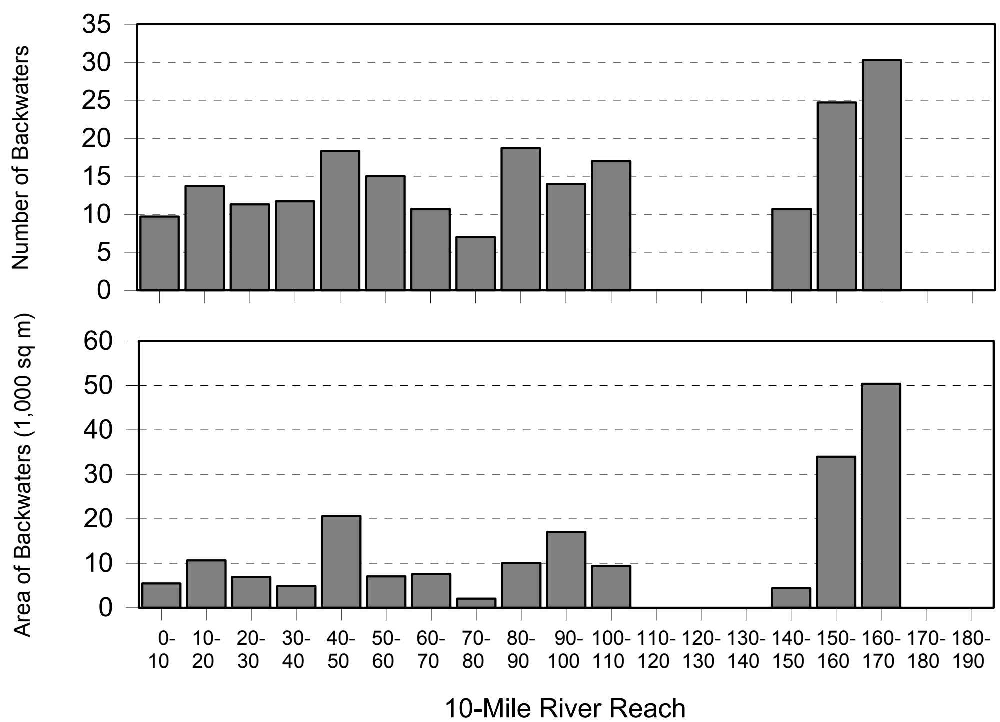


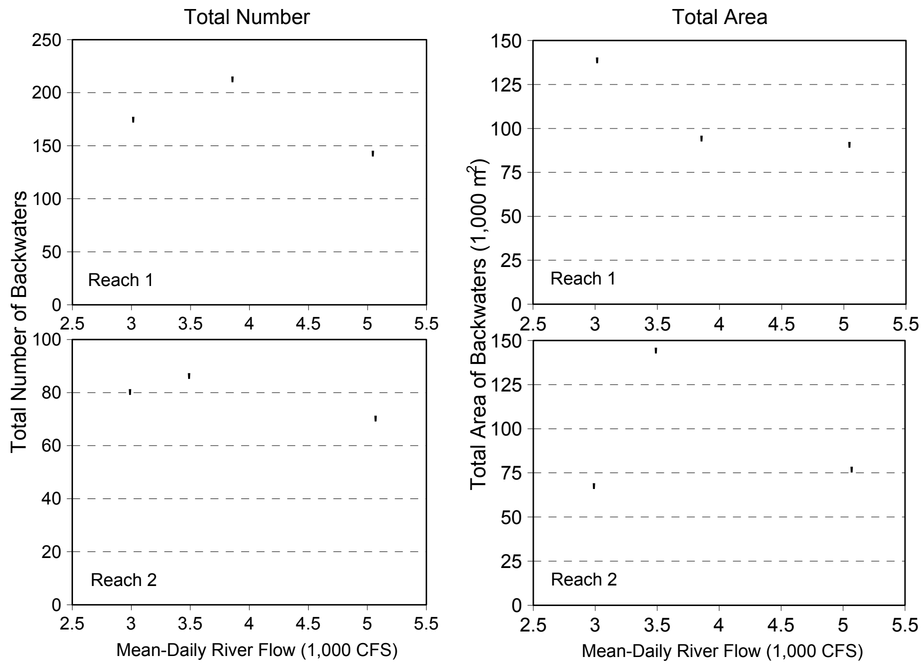
FIGURE 2.13. — Average number (top) and average size (bottom) of backwaters in 10-mi subreaches of the two reaches sampled by autumn ISMP seining for YOY Colorado pikeminnow. Data were summarized from interpretation of aerial videography and are averages of data collected in 1989–1991 at flows ranging between 3,000 and 5,000 cfs (compiled from Table A-5 in McAda 1993). River mile 0 is the mouth of the Green River.

upstream end as water flows decrease after snowmelt runoff ends (Osmundson et al. 1995; Pitlick et al. 1999). Upper-river backwaters are large (16–32 ft wide) and often have gravel and cobble substrates covered with variable depths of silt. In contrast, backwaters downstream from Moab are smaller and usually formed as indentations or depressions in sand bars that are common in the lowest-gradient reach of the river. The most common types of backwaters in the lower river are created by scour channels (formed by the erosion-deposition cycle of small channels behind large alternating sand bars) and migrating sand waves (formed by movement of adjacent migrating sand waves [Trammell and Chart 1999b]). Backwaters created by scour channels tend to be deeper and more permanent than those created by migrating sand waves (Trammell and Chart 1999b); however, substrate in both backwater types is predominately sand and silt. Backwaters downstream from Moab contain the highest densities of age-0 Colorado pikeminnow found in the Colorado River (Section 3.2.2). River gradient and mean substrate size are very similar to reaches of the Green River that also contain high densities of small Colorado pikeminnow (Tyus and Haines 1991; Rakowski and Schmidt 1997).

River flow affects the number and surface area of backwaters in the lower Colorado River (McAda 1993; Trammell and Chart 1999b; Figure 2.14), but the relationship is variable. Backwater number and size tends to be greatest at flows between 3,000 and 4,000 cfs. Backwater number and total surface area declines when flows exceed 4,000 cfs, but backwaters are found at all flows. The minimum level of backwater habitat necessary for a successful Colorado pikeminnow year class cannot be determined based on the available information, but stable backwater habitat is critical to growth and survival of small Colorado pikeminnow (Section 2.2.2).

In the Green River, Rakowski and Schmidt (1997) concluded that establishing a single target flow to maximize backwater habitat every year is not feasible because bar topography, and therefore backwater availability, changes in response to peak flow. They showed that inter-annual variation in backwater location and size is determined by a combination of antecedent flows and river flows at the time of observation. High spring flows do not increase backwater number or area in the year that they occur, but they are critical for persistence of backwaters of sufficient size and quality for YOY Colorado pikeminnow habitat in subsequent years. Trammell and Chart (1999b) concluded that deep backwaters created by chute channels are preferred habitats for YOY Colorado pikeminnow in the Colorado River, primarily because of their depth and persistence from year to year. Chute channels are formed by the erosion-deposition cycle of small channels behind large alternating sand bars (Rakowski and Schmidt 1997). They are scoured out during floods and revealed by receding water levels. These backwaters tend to accumulate fine sediments during extended periods without scouring flows, which reduces habitat quality, and eventually, habitat quantity. Regular flushing flows are necessary to remove these sediments or the backwaters become filled and stabilized by vegetation (Osmundson and Kaeding 1991; Van Steeter 1996) which requires even higher flows to mobilize the sediments and maintain the backwater (Van Steeter 1996; Pitlick and Van Steeter 1998; Van Steeter and Pitlick 1998; Section 2.2.2).

A



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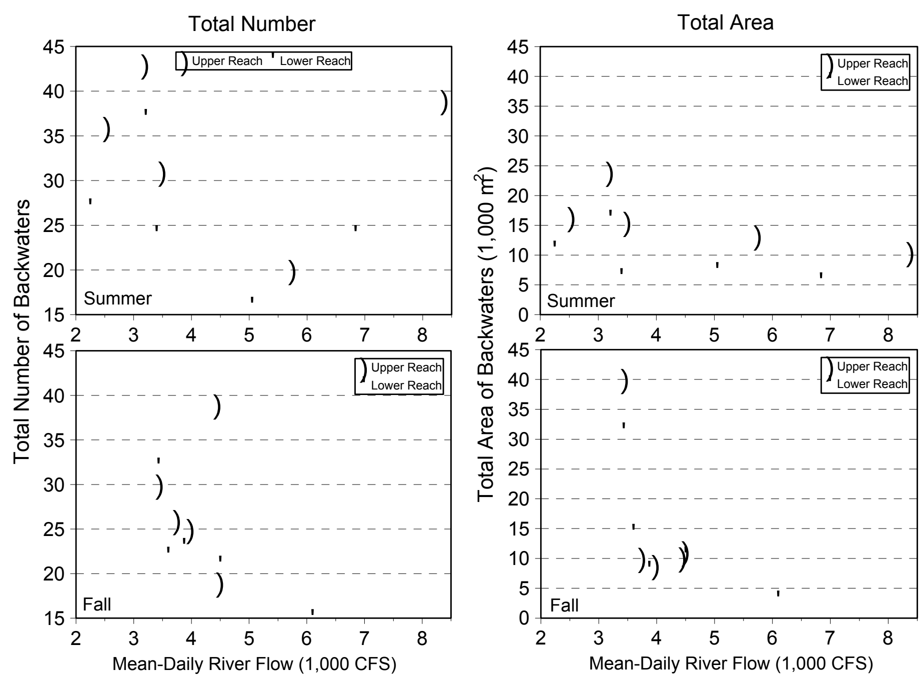

FIGURE 2.14. — Relationships among backwater area (right), total number of backwaters (left), and river flow in the Colorado River: A — autumn, 1989–1991 (McAda 1993); B — summer and autumn, 1992–1996 (Trammell and Chart 1999b). River reaches depicted in the Figures: A, Reach 1 = RM 0–110, Reach 2 = RM 140–170; B, upper = RM 55–65, lower = RM 20–30.

2.2.2 Influence of Water Development on Sediment Transport and Channel Maintenance

As described in Section 2.1.2, peak runoff flows have been significantly reduced in both the Colorado and Gunnison rivers and base flows have increased in reaches that are not depleted by irrigation diversions. These changes are typical of those in rivers modified by reservoir construction and water diversions (e.g., Vanicek et al. 1970; Williams and Wolman 1984; Dawdy 1991; Ligon et al. 1995; Collier et al. 1996). Changes in the hydrology of rivers after reservoir construction have consequences that affect the function of the riverine ecosystem by reducing floodplain connectivity and simplifying main-channel habitats because the intensity, frequency, and duration of river flows sufficient to maintain natural function are reduced (Stanford et al. 1996; Poff et al. 1997). These changes in turn often negatively effect the entire ecosystem — including invertebrates, fish, and riparian vegetation (Stanford et al. 1996; Poff et al. 1997).

Pitlick et al. (1999) documented large-scale morphological changes that have occurred in parts of the Gunnison (lower 60 mi) and Colorado rivers (15-mile reach, 18-mile reach, and Ruby-Horsethief Canyon) by comparing aerial photographs taken in 1937, 1954, 1968, 1993, and 1995. The largest changes were in the 15- and 18-mile reaches where the Colorado River is largely unconstrained and still free to move about the floodplain (Pitlick et al. 1999). Although main-channel and side-channel area increased in some river segments, the overall trend was a decrease in surface area with main-channel area decreasing by 15%, backwater area decreasing by 9% and side-channel area decreasing by 26% (Pitlick et al. 1999). The reduction in side-channel habitat may be especially important because side channels increase habitat diversity even though they compose a small percentage of the river. Complex river reaches (i.e., multi-thread reaches) provide a variety of habitats in a small area and are preferred over single-thread reaches by adult Colorado pikeminnow (Section 3.2.2). The 15- and 18-mile reaches provide most side-channel habitat in the Colorado River (Pitlick and Cress 2000) and contain a much higher number of adult Colorado pikeminnow than other, much longer reaches of the river (Section 3.2.1).

Change in channel area of the Gunnison River was less than observed for the Colorado River, but results were probably underestimated because of large differences in river flow when the two sets of aerial photographs were taken (Pitlick et al. 1999). Also, the Gunnison River is more incised than the Colorado River and less change would be expected. Pitlick et al. (1999) documented little change in main-channel and side-channel area, but showed a 15 % decrease in island area between 1937 and 1995.

Channel narrowing has also occurred in the Green River where bankfull channel width has decreased by about 10% in the Uintah Basin, Utah because of reduced peak flows after construction of Flaming Gorge Dam (Andrews 1986), and by up to 27% in Canyonlands National Park because of reduced flows and bank stabilization by tamarisk (*Tamarix* spp.; Graf 1978)

Some of the loss in fish habitat in the 15- and 18-mile reaches may be related to construction of levees and placement of riprap along the river to prevent flooding and bank erosion in areas with human habitation or use. However, revetments are not as common as might be expected and most of the river is still free to move laterally within its floodplain when flows are sufficient for it to do so (Pitlick and Cress 2000).

Peak flows have decreased significantly in the Gunnison and Colorado rivers since the 1950s, but sediment input to the system apparently has not (Pitlick et al. 1999; Pitlick and Cress 2000). Pitlick and Cress (2000) described the process by which these two interacting factors could reduce channel complexity because side channels gradually filled with sediment that the river could no longer carry through the system:

> "Side channels are characterized by lower flow depths and lower flow velocities than the main channel, thus even under natural conditions their sediment transport capacity is less than the main channel. If, as we have indicated in earlier work (Pitlick et al. 1999), the amount of sediment delivered to these reaches has not changed appreciably, but the river has lost some of its ability to carry this sediment, then whatever it cannot carry will be stored somewhere in the channel. Side channels are the likely sites of storage because they have a lower sediment transport capacity. It is also true that flows through side channels are more ephemeral. Side channels are topographically higher than the main channel, and they are not inundated as often — some side channels may experience flow every year, while others may not experience flow for several years, and then perhaps only for a few days. This allows sediment to build up on the bed, and increases the likelihood that vegetation will colonize the deposits and permanently stabilize them. Vegetation establishment promotes further deposition until, eventually, the side channel has filled to the level of the floodplain."

Osmundson and Kaeding (1991) documented backwaters in the 15-mile reach that became filled with sediment that was not displaced during several consecutive years of low runoff. Lack of flushing flows allowed vegetation to become established, which stabilized the bank and required even higher flows to move the material than would have been required before the vegetation became established. This phenomenon was also documented by Van Steeter (1996) who described the mouth of a backwater filled with sediment that supported a dense mat of cattails and grasses that was not displaced during the higher-than-average runoff in 1993. The sediment was subsequently scoured from the mouth of the backwater by higher runoff flows in 1995 (Van Steeter 1996). Pitlick and Van Steeter (1998) showed that channel changes that occur during extended periods of below-average runoff are difficult to reverse after snow-melt runoff returns to average or above average levels.

Movement of significant amounts of fine sediment (silt and sand) from within the river bed generally requires that framework particles are moved, i.e., movement of gravel along the bed to allow the finer sediments to be picked up and moved downstream by the river (Pitlick and Van Steeter 1998; and references therein). Geomorphologists refer to two important transport phases that provide different levels of particle movement along the river bed — initial motion and significant motion (Pitlick and Cress 2000; and references therein). The following definitions are excerpted from Pitlick and Cress (2000):

Initial Motion — "Initial motion [also referred to as critical discharge] denotes the onset of bed load transport.... In the initial motion phase very few particles on the streambed are moving and transport rates are low. This phase is nonetheless very important to maintaining [the interstitial spaces in gravel and cobble bars] because it marks the point at which framework particles start moving and fine sediment begins to be flushed from the bed."

Significant motion — "Significant motion is characterized by continuous movement of most all particles on the bed."

As the definition implies, initial motion is the transport level that begins to remove fine sediments from the channel bed, including the interstitial spaces of cobble bars that provide spawning habitat for Colorado pikeminnow and razorback sucker (sections 3.2.3 and 3.3.3). Flows need to exceed initial motion to remove substantial amounts of fine sediment from the bed. The interstitial spaces in gravel and cobble bars also provide habitat for periphyton, invertebrates, and other organisms that form the basis of the food chain in the Gunnison and Colorado rivers (Section 2.2.3).

Pitlick and Cress (2000) showed that significant motion was approximately equal to bankfull discharge in the Gunnison River and in the Colorado River upstream from the mouth of the Dolores River. However, significant motion probably occurs at flows less than bankfull discharge in the Colorado River downstream from the Dolores River because of the wide channel and smaller substrate particles found there (Pitlick and Cress 2000). River flows that reach bankfull flow move most particles on the bed and are often channel-forming flows that shift cobble and gravel bars, scour vegetation, and maintain side channels. These flows maintain complex channel areas that provide a suite of important habitats for Colorado pikeminnow and razorback sucker (Sections 3.2.2 and 3.3.2).

Pitlick et al. (1999) calculated river discharges that produced initial motion and bankfull flow in the Gunnison River (with flow referenced to the USGS gage near Grand Junction) and in the Colorado River immediately downstream from their confluence (18-mile reach and Ruby-Horsethief Canyon; referenced to the USGS gage near the Colorado-Utah state line). Figure 2.15 depicts the river discharge that initiates the two transport levels (initial motion, $\boldsymbol{Q}_c$ and bankfull flow $\boldsymbol{Q}_b$) at 1-mi intervals in the Gunnison River. Horizontal lines indicate median values for the two threshold levels ($\boldsymbol{Q}_c$ 8,070 cfs and $\boldsymbol{Q}_b$ 14,350 cfs). However, as denoted by the scatter of points for the individual cross sections, the two threshold levels varied widely along the river (Figure 2.15). Figure 2.16 rearranges the data as the cumulative percentage of 54 different cross sections along the Gunnison River reaching the two different threshold levels of particle motion. Initial motion occurs at one cross section at 4,660 cfs, but it is not reached in the entire river until discharge exceeds 12,700 cfs. Bankfull flow occurs at one cross section at about 5,000 cfs, but it is not reached in the entire river until discharge exceeds 28,000 cfs.

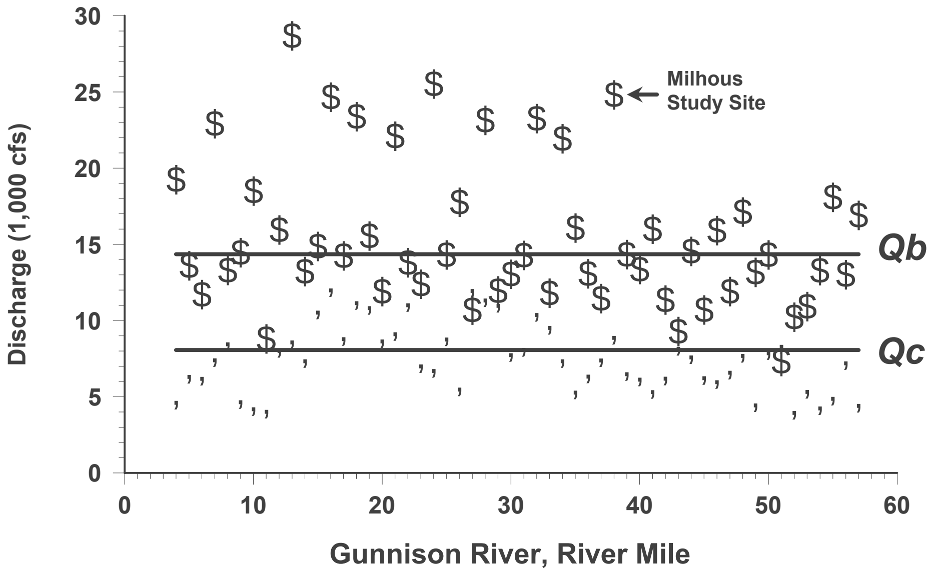

FIGURE 2.15. — Estimates of river flows that trigger initial motion, Q_c (■), and bankfull flow, Q_b (□), at 54 cross sections on the Gunnison River (modified from Figure 28b in Pitlick et al.[1999]). River mile 0 is the mouth of the Gunnison River. Horizontal lines equal median values for the two threshold flows (Q_c – 8,070 cfs; Q_b – 14,350 cfs). Arrow indicates a 1-mi reach studied by Milhous (1998).

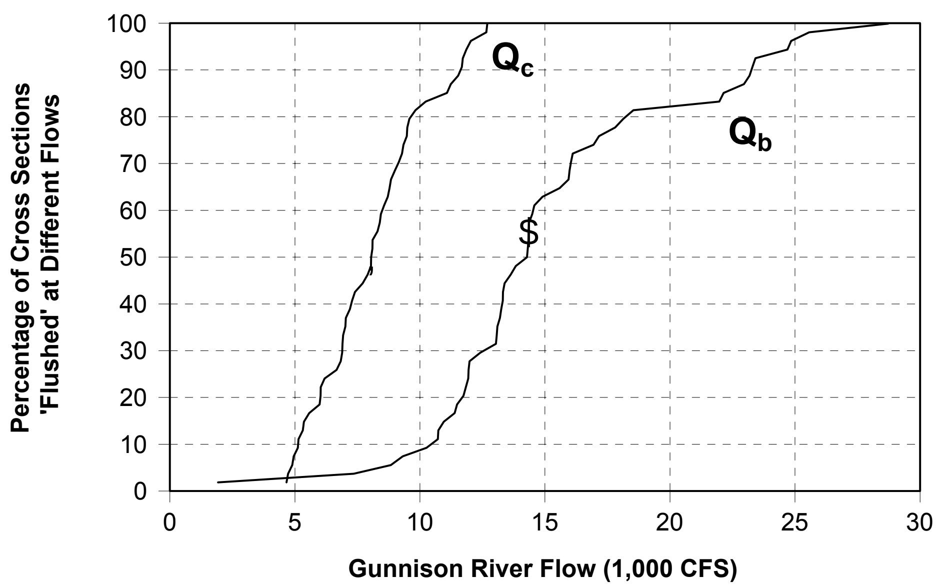

FIGURE 2.16. — Cumulative percentage of 54 cross sections in the Gunnison River reaching two threshold levels of particle motion — initial motion (Q_c) and bankfull discharge (Q_b). Data are reorganized from Figure 2.15; median values are indicated (Q_c, ■ and Q_b, □).

As in the Gunnison River, discharges that corresponded to initial motion and bankfull flow in the Colorado River varied among transects (Figure 2.17; Pitlick and Cress 2000). Flows that triggered initial motion were consistent up- and downstream from Westwater Canyon, with median flows of 18,538 and 19,986 cfs. However, bankfull flows are more variable, with much higher flows required in the lower river. The median bankfull flow upstream from Westwater Canyon is 35,098 cfs, whereas median bankfull flow downstream from Westwater Canyon is 58,615 cfs. The increasing values for bankfull discharge in the lower river correspond to increasing channel width and depth. Recall that significant motion equals bankfull discharge upstream from the mouth of the Dolores River, but is probably less than bankfull discharge in the lower river.

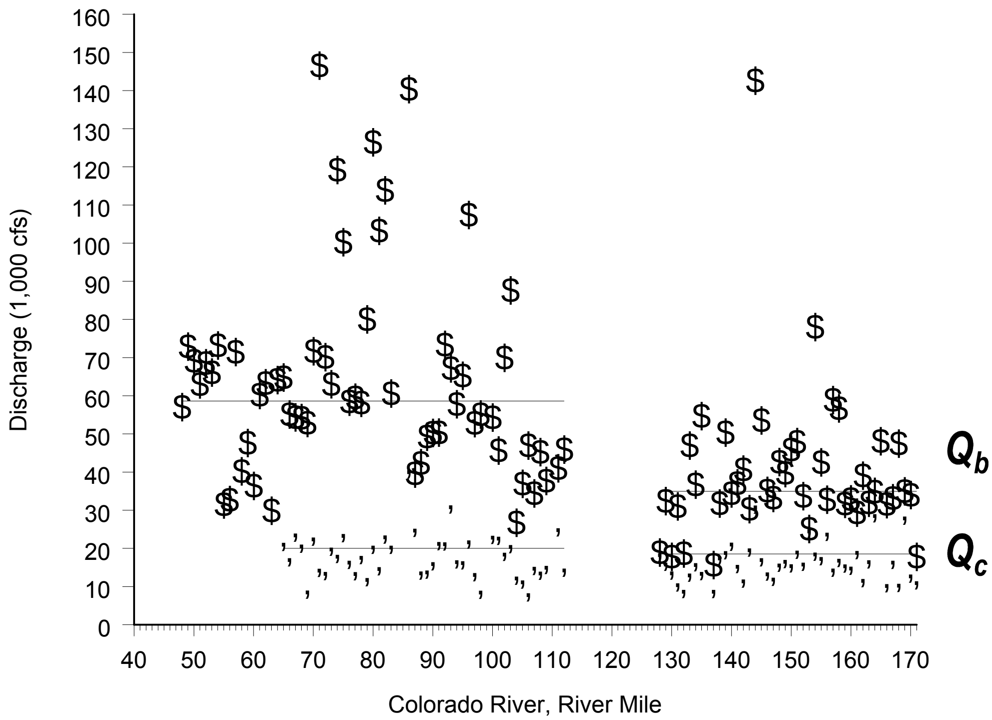

FIGURE 2.17. — Estimates of river flows that trigger initial motion, Q_c (■), and bankfull flow Q_b (□), at 104 cross sections on the Colorado River downstream from its confluence with the Gunnison River; RM 0 is the mouth of the Green River (data from Figure 25 in Pitlick and Cress [1999]). The river within Westwater Canyon was not surveyed. Horizontal lines equal median values for two distinct geomorphic reaches in the study area: mouth of Gunnison River downstream to Westwater Canyon (RM 128–171) — Q_c, 18,538 cfs and Q_b, 34,957 cfs; and downstream from Westwater Canyon (RM 48–112) — Q_c, 19,986 cfs and Q_b, 58,615 cfs.

Figure 2.18 shows the cumulative percentage of transects in the Colorado River downstream from the Gunnison River reaching the two threshold levels as river flow increases. On a river-wide basis, the median value for initial motion is 19,032 cfs and the median value for bankfull flow is 48,127 cfs. All transects have reached initial motion at 36,500 cfs.

Milhous (1998) conducted an intensive study of a 1-mi-long segment of the Gunnison River near Dominguez Flats (RM 38). His study used the same basic methodology as Pitlick et al. (1999); however, he made measurements at about 20 cross sections in his study area over a 3-yr period. Milhous estimated several sediment transport levels (also referenced to the USGS gage near Grand Junction) for the Gunnison River, including: (1) flush fine sediments from the surface of the bed — 12,535 cfs; (2) prevent fine sediments from being deposited in riffles — 950 cfs; (3) remove gravel from pools — 17,000 cfs; and (4) scour side channels — 7,415 cfs. Milhous's transport levels were technically different from initial motion and

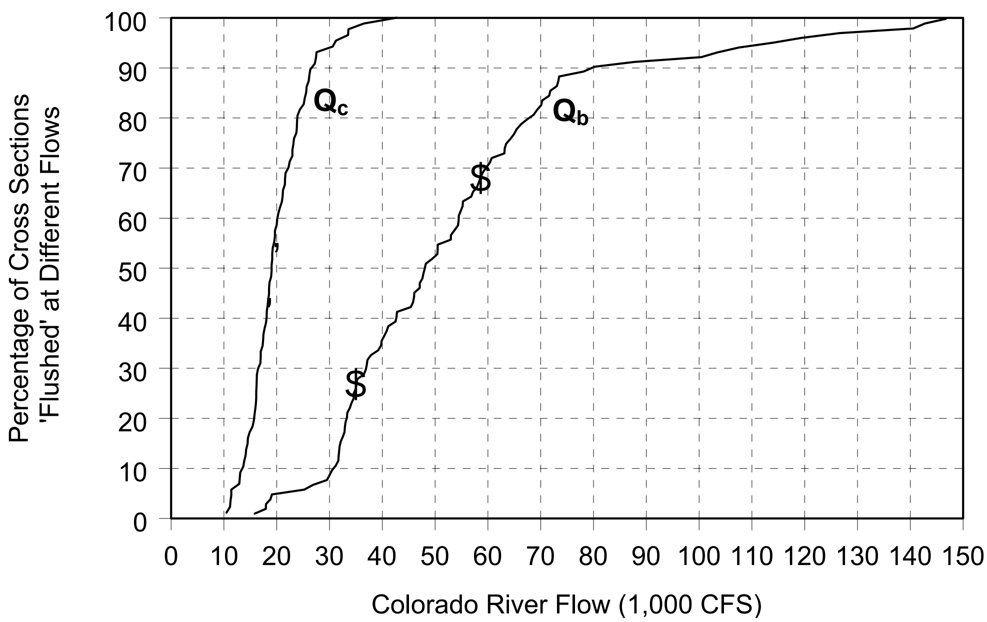

FIGURE 2.18. — Cumulative percentage of 104 cross sections in the Colorado River reaching two threshold levels of particle motion — initial motion (*Q_c*)and bankfull flow (*Q_b*). All cross sections depicted are downstream from the confluence with the Gunnison River (≤RM 171). Median values for two river reaches are indicated: mouth of Gunnison River downstream to Westwater Canyon (RM 128–171) — *Q_c*, 18,538 cfs and *Q_b*, 34,957 cfs; and downstream from Westwater Canyon (RM 48–112) — *Q_c*, 19,986 cfs and *Q_b*, 58,615 cfs. Data were reorganized from Figure 2.17.

bankfull flow estimated by Pitlick et al. (1999). However, the concept of flushing fine sediments from the bed is equivalent to Pitlick et al.'s concept of initial motion (J. Pitlick, personal communication). Milhous's estimate of 12,500 cfs was higher than the median value determined by Pitlick et al. (1999). However, Pitlick et al.'s estimates varied among cross sections and their estimate of bankfull flow for their cross section near Milhous's study site was one of the highest estimates for the reach (noted on Figure 2.15). This difference is because the bed material in Milhous's study section was apparently larger than average in the Gunnison River and higher flows were necessary to move framework particles so that fine particles could be flushed from the river bed (Pitlick et al. 1999). Milhous's concept of keeping fine sediments from settling on the bed at flows of 950 cfs or greater becomes most important during, and immediately following, spawning by Colorado pikeminnow. After interstitial spaces are cleared of fine sediments by higher flushing flows, a minimum of 950 cfs prevents fines from smothering embryos that might have been deposited in the gravel.

Transport levels discussed above perform functions critical to maintaining the ecological health of the rivers; however, their frequency of occurrence has been reduced in both rivers because of water development. Table 2.5 presents the frequency of the two transport levels in the Gunnison River during three water-development phases discussed above (data were compiled using USGS records from the gages noted). Flows that created initial motion in the Gunnison River occurred in 82 (9,409 cfs) to 93% (6,126 cfs) of the years before construction of Taylor Park Reservoir, but their frequency declined to 38 to 69% of the years after completion of Blue Mesa Reservoir. The largest decrease occurred in the frequency of flows that created initial motion in the longest part of the river (9,600 cfs), which declined from a frequency of 3 out of 4 yr to 1 in 3 yr. This section of the Gunnison River is heavily used by Colorado pikeminnow and contains a presumed spawning area (sections 3.2.1 and 3.2.2). Median flows for bankfull flow occurred in about 60% of the years before Taylor Park Reservoir was built, but frequency declined to about 20% of the years after Blue Mesa Reservoir was completed (Table 2.5). The duration of these flows (i.e., the number of days each year that the critical flow is reached or exceeded) has also declined substantially (Table 2.5).

Milhous (1998) calculated a sediment transport capacity index (STCI) to characterize changes in the ability of the Gunnison River to move sediments based on changes in runoff patterns caused by reservoir construction and other factors. The index is based on the critical discharge for a specific sediment-transport related process and the sum of the daily discharge values for the river (see Milhous [1995] and Milhous [1998] for a complete description of STCI and how it is calculated). River flows with STCI adequate to flush the surface of the bed occurred about 1 in 1.5 yr before Taylor Park Reservoir was built but declined in frequency to about 1 in 5 yr after construction of Blue Mesa Reservoir (Figure 2.19; Table A.25). Likewise, flows with STCI adequate to scour gravel and sand from pools of the Gunnison River declined in frequency from 1 in 2 yr before Taylor Park to 1 in 7 yr after Blue Mesa Dam was completed (Figure 2.20; Table A.26).

TABLE 2.5. — Water-development related change in frequency and duration of Gunnison River and Colorado River flows related to median sediment-transport levels identified by Pitlick et al. (1999). Analysis based on flows measured at USGS gages for three time periods.

Transport level and equivalent median river flow (cfs)	Average (range) number of days per year that target flows were equaled or exceeded			Frequency of years that target flows were equaled or exceeded for at least 1 d		
	Pre Taylor[a]	Pre Aspinall[b]	Post Aspinall[c]	Pre Taylor[a]	Pre Aspinall[b]	Post Aspinall[c]
Gunnison River[d]						
Initial motion						
6,126[e]	49.3 (0–75)	40.2 (0–91)	25.0 (0–88)	93%	93%	69%
9,409[e]	30.8 (0–61)	19.9 (0–60)	9.3 (0–69)	82%	62%	38%
6,930[e]	44.1 (0–70)	33.9 (0–87)	20.2 (0–78)	93%	90%	63%
8,073[f]	37.4 (0–63)	26.6 (0–71)	14.5 (0–74)	93%	76%	44%
Bankfull flow						
14,062[e]	11.6 (0–39)	7.0 (0–37)	2.8 (0–30)	64%	45%	6%
14,620[e]	10.4 (0–34)	5.7 (0–33)	2.1 (0–26)	64%	45%	6%
13,310[e]	13.1 (0–40)	8.7 (0–41)	3.4 (0–34)	68%	48%	6%
14,325[f]	11.0 (0–37)	6.5 (0–35)	2.5 (0–29)	64%	45%	6%
Colorado River, 18-Mile Reach and Ruby-Horsethief Canyon[g]						
Initial motion						
18,538		25.3 (0–72)	22.4 (0–69)		71%	61%
Bankfull flow						
34,957		6.1 (0–35)	4.4 (0–53)		29%	21%
Colorado River downstream from Westwater Canyon[h]						
Initial motion						
20,000	47.4 (0–70)	35.0 (0–77)	24.7 (0–78)	89%	89%	66%
Bankfull flow						
58,600	1.5 (0–18)	0.2 (0–5)	0.3 (0–8)	17%	7%	6%

[a] Gunnison River calculations were based on 1897–1899, 1902–1906, and 1917–1936. No data are available for the Colorado River at the Colorado-Utah state line. Lower Colorado River calculations included 1914–1917, 1923–1936.
[b] Gunnison River and lower Colorado River calculations included 1937–1965; however, the gage on the Colorado River at the Colorado-Utah state line was not established until 1951, so 1951–1965 was used.
[c] All calculations included 1966–1997.
[d] Gunnison River near Grand Junction, (USGS gage 09152500).
[e] Median flows for reaches depicted in Figure 2.15 (RM 4–12, RM 13–38, RM 39–57, repectively).
[f] Median flow for entire river (RM 4–57).
[g] Colorado River at Colorado-Utah state line (USGS gage 09163500).
[h] Colorado River near Cisco (USGS gage 09180550).

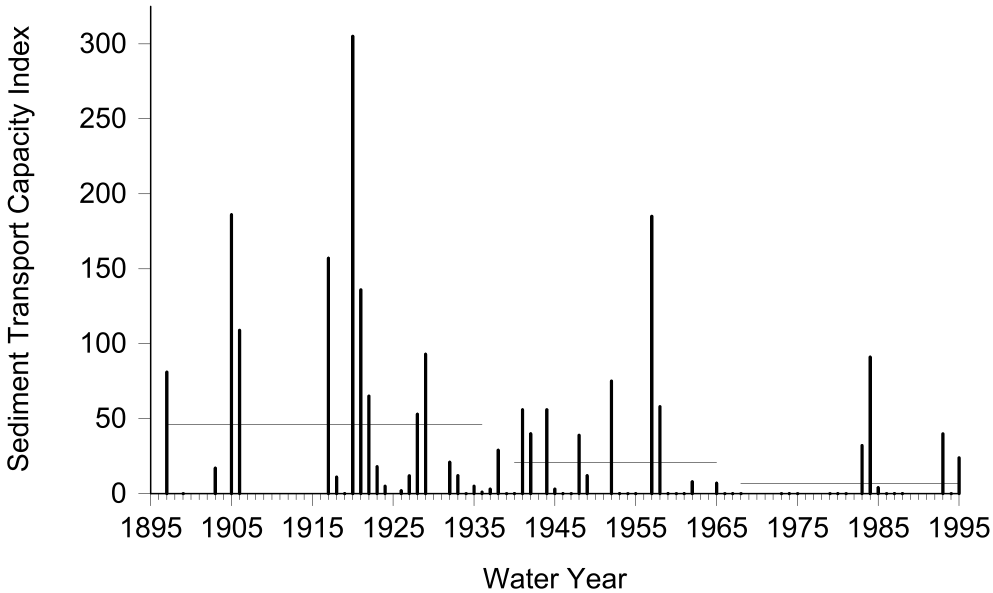

FIGURE 2.19. — Changes in the annual sediment transport capacity index for the Gunnison River based on surface flushing criteria. The critical discharge was 13,000 cfs. Figure 5 in Milhous (1998).

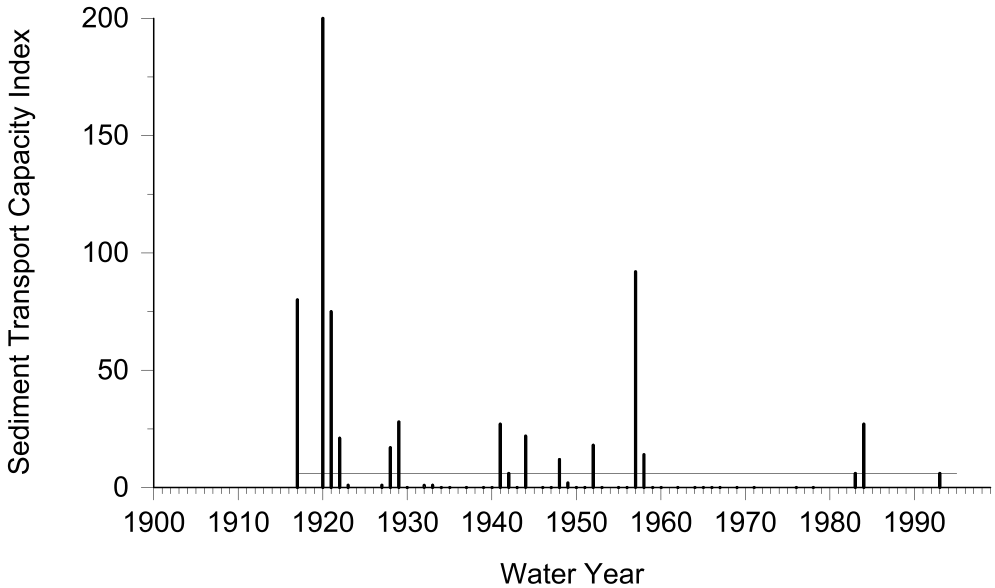

FIGURE 2.20. — Changes in the annual sediment transport capacity index for the Gunnison River based on scouring gravel and sand from pools. The critical discharge was 17,400 cfs. Figure 10 in Milhous (1998).

The period of record for the Colorado River at the USGS gage near the Colorado-Utah state line does not begin until 1951, so the ability to analyze flow changes in the Colorado River immediately downstream from the confluence with the Gunnison River is limited. Some water development had already occurred in the basin by the time flow measurements began, so predevelopment conditions can not be determined at that gage. Nonetheless, the frequency of years with flows sufficient to reach initial motion declined from 71 to 61% after construction of Blue Mesa Dam, and the frequency of years with flows sufficient to reach bankfull flow declined from 29 to 21%. The effect of water development on Colorado River flows that determine the two critical transport levels in the upper Colorado River can probably best be estimated by analysis of discharge data from upstream of the Gunnison River. Osmundson and Scheer (1998) calculated that frequency of years with flows sufficient to reach initial motion (10,000 cfs; as calculated by Pitlick et al 1999) in the 15-mile reach declined from 100 to 77% and the frequency of years with flows that create bankfull flow (20,000 cfs) declined from 77 to 34% over two water-development periods (1902–1942 and 1954–1997).

The period of record is more complete at the USGS gage near Cisco which describes flows in the Colorado River downstream from Westwater Canyon. The median flow for initial motion in that reach is 20,000 cfs (Pitlick and Cress 2000); the average number of days that level was equaled or exceeded declined from 47.4 before 1937 to 24.7 after 1966 (Table 2.5). The frequency of years in which 20,000 cfs was reached for at least 1 d declined from 9 in 10 to about 2 in 3. The median level for bankfull flow in the lower river is about 58,600 cfs. That level is high because of several transects in the lower river with bankfull flows that exceed the maximum river flow ever recorded at the gage. Some of the highest values may be erroneous because of extreme channel width at the transect sites, but most reflect the true requirements of the lower river (Pitlick and Cress 2000). Flows that equaled or exceeded 58,600 cfs occurred in 17% of years before 1936 and in 6–7% of years after 1937. There was no real difference in frequency of occurrence between 1937–1965 and 1966–1997.

2.2.3 Relationship of Fine Sediment to Periphyton and Invertebrate Biomass

Substrate size and volume of interstitial spaces are important variables controlling primary and secondary production in a river system (Lamarra 1999). Bed material composed primarily of fine material provides little habitat for macroinvertebrates because spaces between particles are too small for most organisms. Coarser material provides larger interstitial spaces for benthic organisms, and also provides habitat for egg development and to shelter larval fish for the first few days after hatching. However, even bed material that is largely composed of coarse particles becomes clogged with fine sediments over time, which reduces habitat for macroinvertebrates and egg development. Periodic winnowing of the bed is necessary to remove the fines and rejuvenate the interstitial spaces between the larger particles (Milhous 1973).

Depth-to-embeddedness (DTE) is a measure of the amount of interstitial spaces available in the bed material and is the distance from the top of the particles on the bed surface down to the top layer of fine sediments in which the larger material is embedded (Osmundson and

Scheer 1998). This depth provides a standard measurement of the available space for benthic organisms along the bed of a river.

Lamarra (1999) measured DTE in the Colorado and Gunnison rivers in spring and autumn 1994–1995. Spring samples were taken prior to spring runoff and autumn samples were taken after the river reached base flow in September. Mean river-wide DTE values were significantly greater in riffles than in runs on all sampling dates for both rivers (ANOVA, $P<0.05$; Figure 2.21). Mean values averaged about 5 cm greater in riffles than in runs. Mean DTE for runs in the Colorado River was deeper than runs in the Gunnison River, but values for riffles were similar between the two rivers. Although mean DTE varied among rivers and habitats, temporal variation was similar in both habitats in both rivers. Combined DTE in the Colorado River increased slightly between spring and autumn 1994 (i.e., following spring runoff) and then declined significantly during the following winter (ANOVA, $P<0.05$; Figure 2.22). However, DTE increased significantly following spring runoff in 1995 (ANOVA, $P<0.05$), reaching an average higher than observed at any time in the study. DTE in the Gunnison River increased (but not significantly) following spring runoff in 1994 (Figure 2.22). It was not measured before spring runoff in 1995, but mean DTE was higher in autumn 1995 than it was in autumn 1994. In general, spring runoff did not play as great a role in maintaining DTE in riffles as it did in runs in both river systems. DTE was most affected by accumulation of fines in runs and pools between runoff events (Lamarra 1999).

Lamarra's (1999) study incorporated data collected in low (1994) and high (1995) runoff years and documented greater DTE following high runoff in 1995 than following low runoff in 1994. However, 1993 was also a high-runoff year that moved large amounts of sediment in the Colorado and Gunnison rivers that had accumulated during a period of consistently low runoff (D. Osmundson, personal communication). Because no measurements were taken prior to 1993's runoff, it is not known how long it might take for sediments to accumulate in the river bed. But it is likely that the winnowing of fine sediments by high flows equal to 1993 would take several years to be completely offset and that DTE in 1994 was higher than it would have been after several years of consistently low runoff.

Lamarra (1999) estimated primary production in the Colorado and Gunnison rivers in 1994–1995 as instantaneous biomass estimates of chlorophyll-*a* (Figures 2.23 and 2.24). His sampling protocol involved taking samples in spring (March) prior to snowmelt runoff, and again in autumn (September) during baseflow conditions (the Gunnison River was not sampled in spring 1995). River-wide means for both rivers were significantly higher in riffles than in runs (ANOVA, $P<0.05$; Figure 2.24). Biomass levels in both riffles and runs were significantly higher in the Gunnison River than in the Colorado River in autumn 1994 and 1995 (ANOVA, $P<0.05$), but not in spring 1995. Biomass estimates for both habitats in both rivers exhibited the same temporal pattern — it increased slightly between spring and autumn 1994, declined over the following winter, and then increased significantly by autumn 1995 (ANOVA, $P<0.05$). The increase between spring and autumn 1995 was much greater than occurred between spring and autumn 1994. As noted in Section 2.1.4, spring runoff was high in 1995 (15% exceedance) and low in 1994 (95% exceedance). DTE was directly related to peak runoff flows.

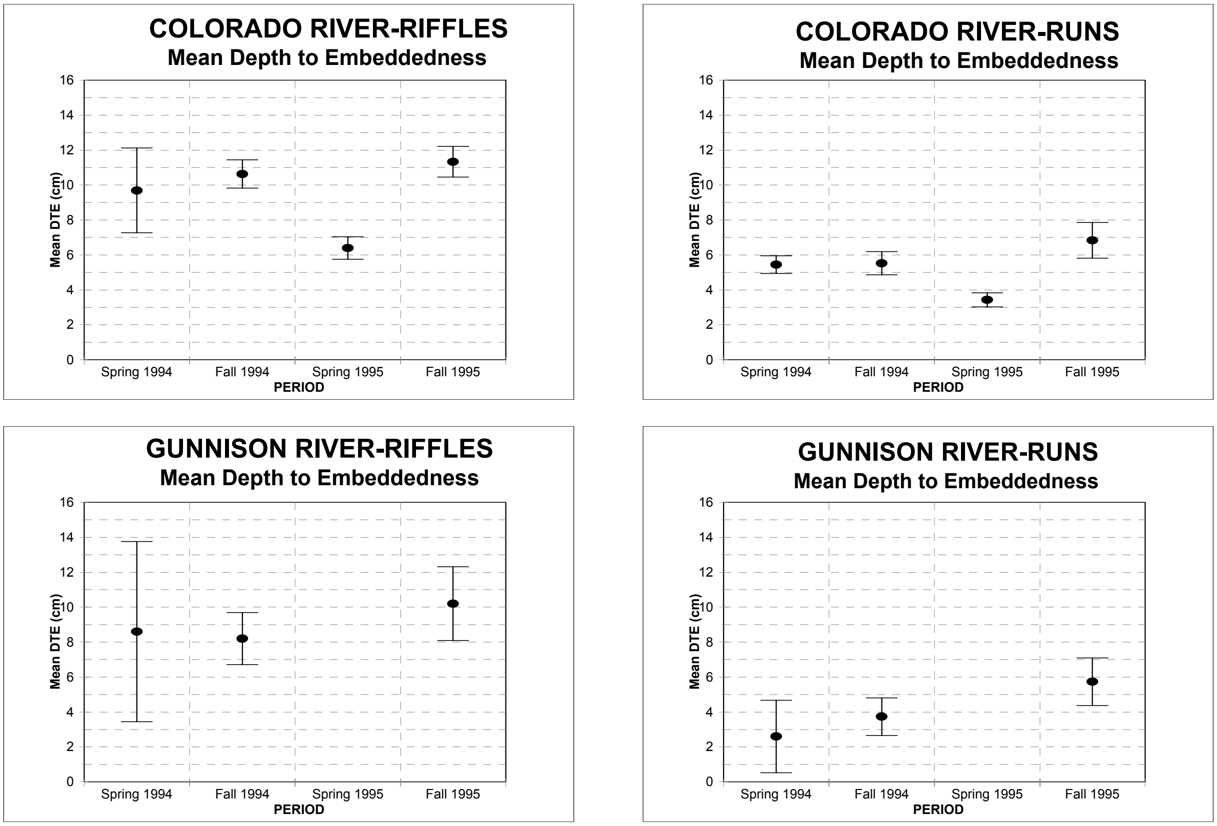

FIGURE 2.21. — Seasonal distribution (mean ± 95% CI) of depth to embeddedness for riffles and runs in the Colorado and Gunnison rivers. Figure 5 in Lamarra (1999).

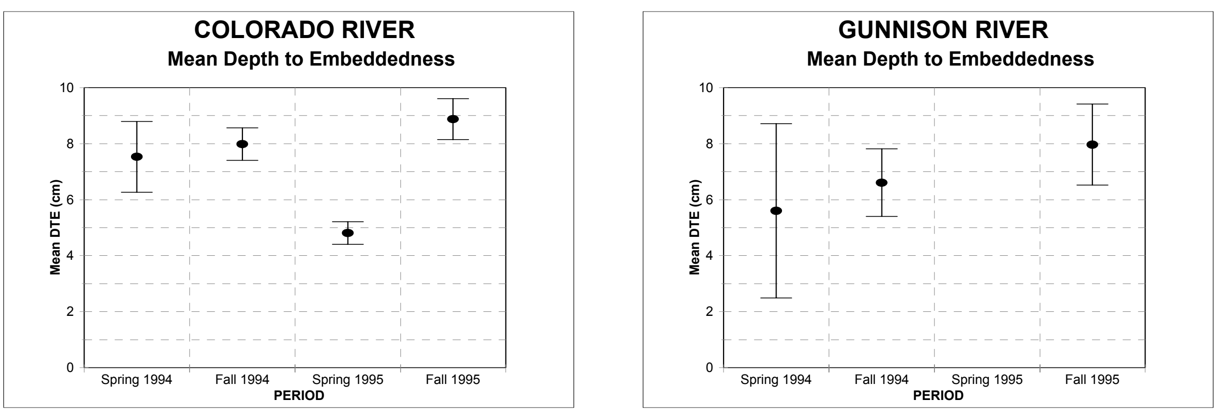

FIGURE 2.22. — Seasonal distribution (mean ± 95% CI) of depth to embeddedness for river-wide substrate samples in the Colorado and Gunnison rivers. Figure 19 in Lamarra (1999).

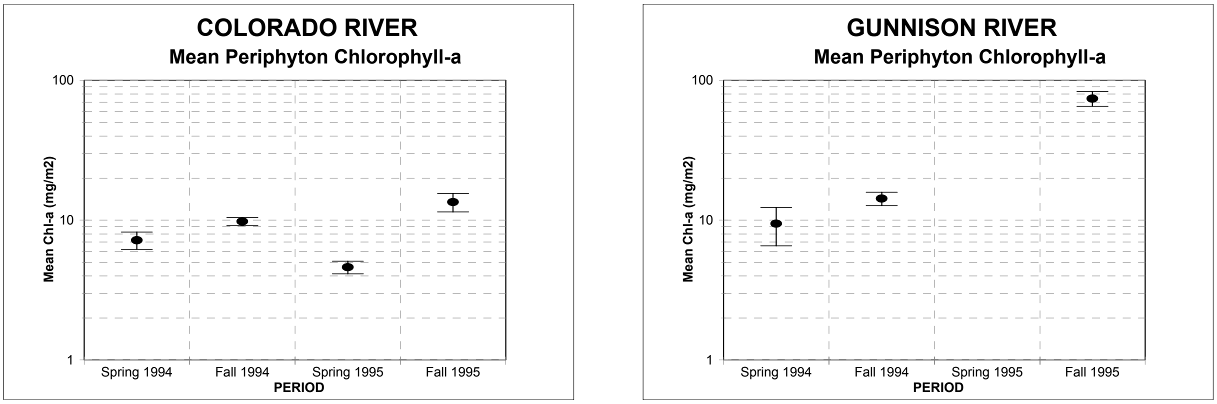

Figure 2.23. — Mean and 95% confidence intervals for periphyton chlorophyll-a values calculated for the river-wide substrate samples in the Colorado and Gunnison rivers, 1994–1995. Figure 12 in Lamarra (1999).

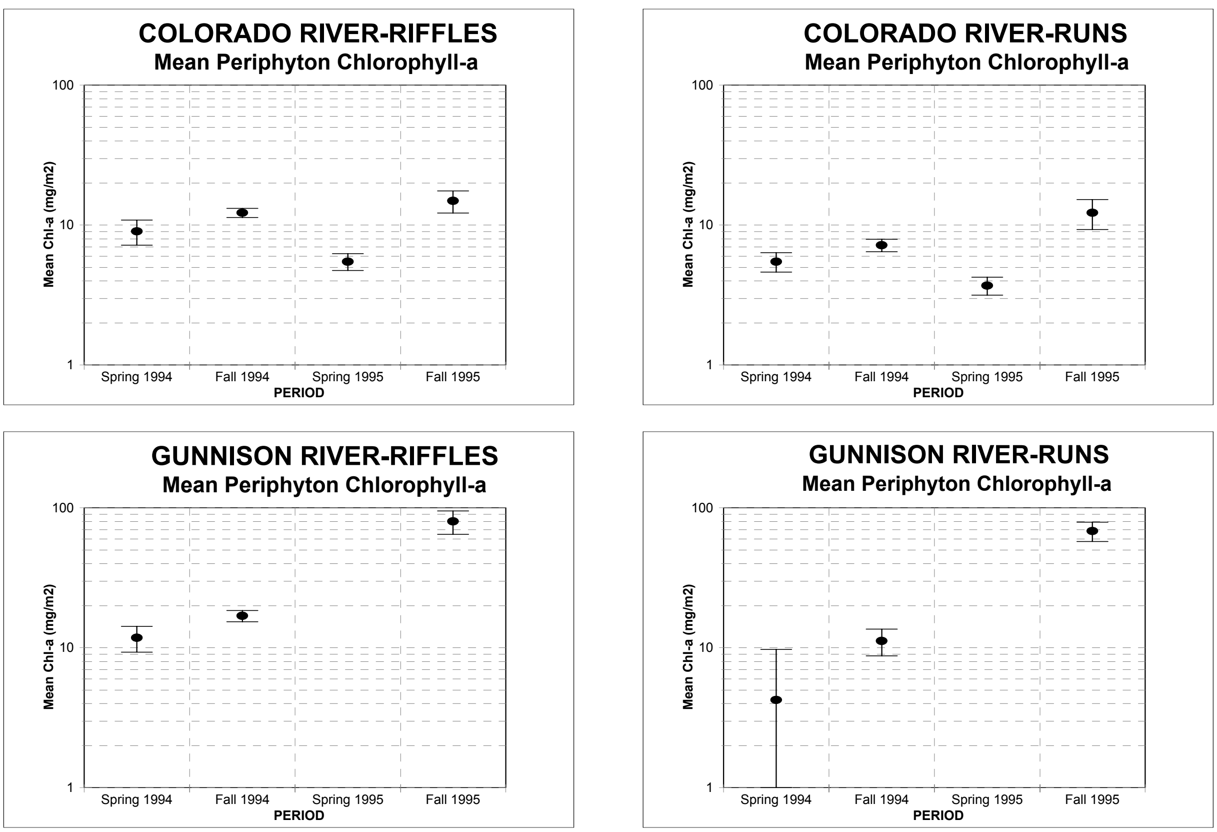

FIGURE 2.24. — Seasonal distribution of periphyton chlorophyll-a for riffles and runs in the Colorado and Gunnison rivers, 1994–1995. Figure 24 in Lamarra (1999).

Lamarra (1999) also estimated standing crops of macroinvertebrates in the Colorado and Gunnison rivers (Figures 2.25 and 2.26). As with periphyton, standing crops of macroinvertebrates were significantly higher in riffles than they were in runs in both rivers (ANOVA, $P<0.05$; Figure 2.26). River-wide macroinvertebrate densities were relatively high in spring 1994, declined through spring 1995, but then rebounded in autumn 1995.

Although riffles had significantly higher levels of periphyton and macroinvertebrates than runs, riffles are a small percentage of habitats available for primary and secondary production in the Gunnison and Colorado rivers (Section 2.2.1). Therefore, even though runs are relatively less productive than riffles, their areal dominance of the Colorado and Gunnison rivers means that most primary and secondary production occurs in runs (Lamarra 1999).

Lamarra's (1999) study was short and thus was not able to investigate long-term change in DTE and associated change in periphyton and invertebrate biomass at one location. Osmundson et al. (2002) used principal components analysis to investigate relationships between DTE and periphyton and invertebrate biomass for the Colorado River. They found significant positive relationships between factor scores describing increasing DTE with both invertebrate and periphyton biomass (Figure 2.27). These relationships were primarily driven by data collected from runs where the greatest variability was found. There is also a significant longitudinal effect associated with the relationships (not depicted) that complicates interpretation of the data. However, DTE and related physical variables were clearly important in determining periphyton and invertebrate biomass in runs.

The biological and physical components of the Gunnison and Colorado rivers are closely interrelated, with high densities of fine substrate materials negatively affecting standing crops of primary and secondary producers in both runs and riffles (Lamarra 1999). More fine sediments are found in runs than in riffles because slower water velocities allow them to settle there first. Because runs and pools are the first places that fine sediments will settle, these habitats need regular flushing to maintain productivity. Regular flushing of all habitats, but especially runs because of their extreme abundance, is important to maintaining primary and secondary production in the Colorado and Gunnison rivers.

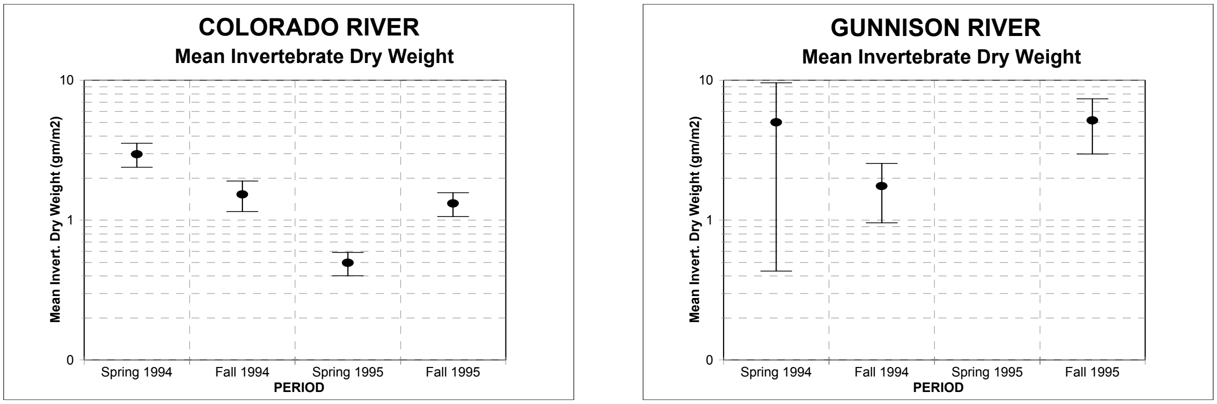

FIGURE 2.25. — Mean and 95% confidence interval of invertebrate dry weights for river-wide samples collected from the Colorado and Gunnison rivers, 1994–1995. Figure 14 in Lamarra (1999).

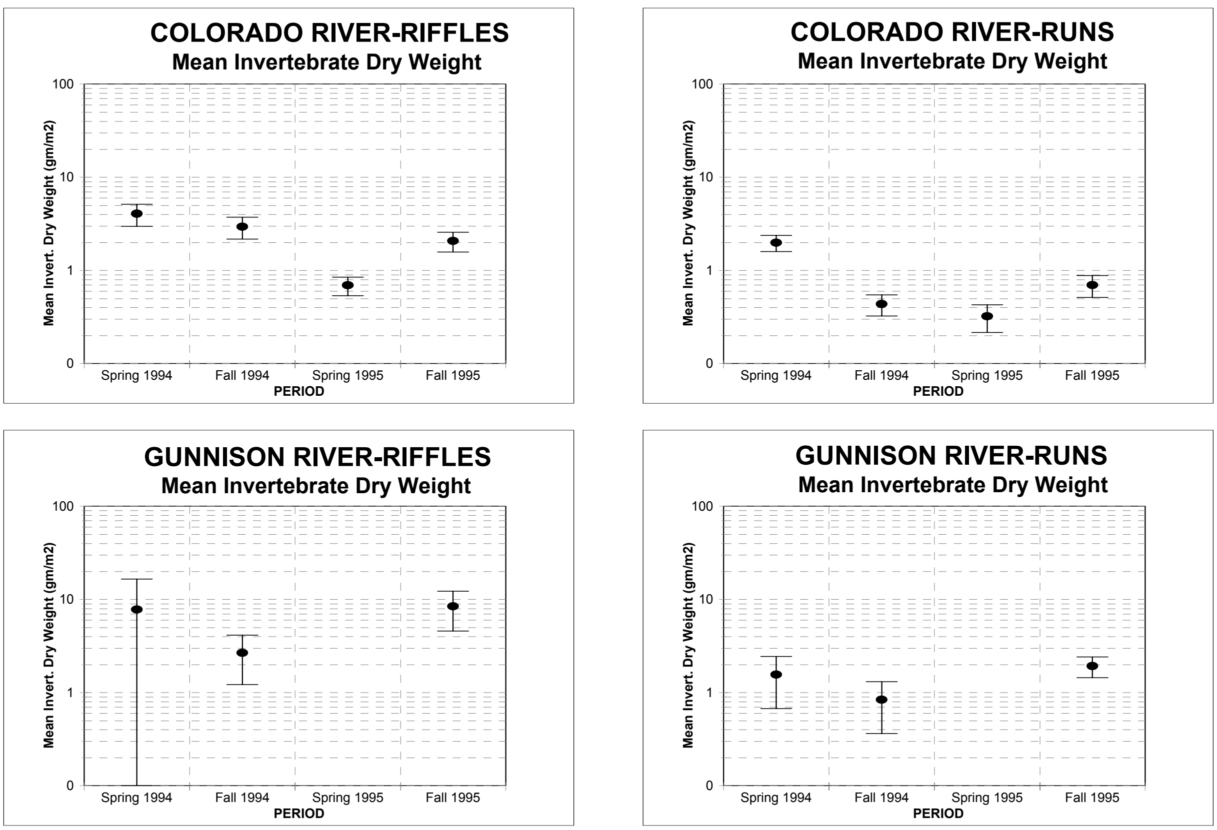

FIGURE 2.26. — Seasonal distribution of invertebrate dry weight for riffles and runs in the Colorado and Gunnison rivers, 1994–1995. Figure 26 in Lamarra (1999).

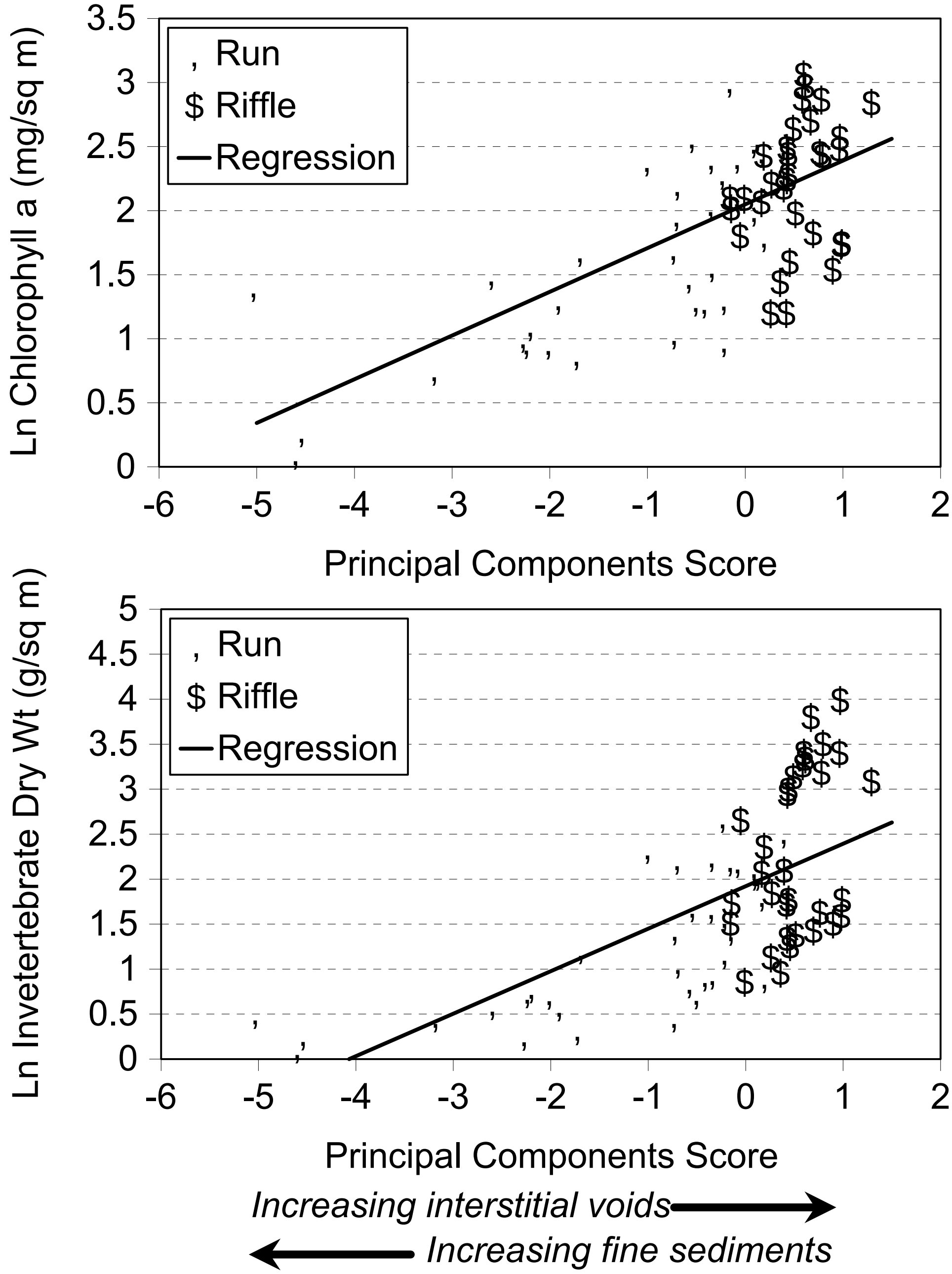

FIGURE 2.27. — Interrelationships between ln chlorophyll-*a* (top), ln invertebrate dry weight (bottom), and principal components scores associated with physical factors measured by Lamarra (1999). Figures 4a and 4b in Osmundson et al. (2002). High factor scores were associated with increasing depth to embededness and higher detrital content and water velocity, whereas low factor scores were associated with increasing amounts of fine sediments (<2 mm). Regressions were significant at *P* < 0.0000001.

2.2.4 Influence of Water Development on Floodplain Inundation

Most of the floodplain habitat within the Gunnison River occurs in the vicinity of Delta between the mouths of the North Fork of the Gunnison River and Roubideau Creek (Irving and Burdick 1995). Limited floodplains occur at scattered downstream locations, but they are small and generally require relatively high flows to be inundated (Irving and Burdick 1995; McAda and Fenton 1998). Floodplains form in alluvial reaches where the river is unconstrained by natural features and is allowed to move across the landscape. Floodplains are highly productive components of riverine ecosystems (summarized by Wydoski and Wick 1998) and serve as important habitats for the endangered fishes. These habitats warm earlier than other parts of the river and provide warm, quiet-water refugia that allow for earlier gonadal maturation by adult Colorado pikeminnow (Section 3.2.3) and razorback suckers (Section 3.3.3) in preparation for spawning. They also provide important habitat for survival and growth of larval razorback suckers (Section 3.3.3).

Irving and Burdick (1995) identified three important bottomlands near Delta: opposite Confluence Park (RM 57.1), Johnson Slough (RM 53.6), and Escalante State Wildlife Area (SWA; RM 50.7–52.3). Staff gages were placed at Confluence Park and Johnson Slough to estimate flows required for flooding to begin: (1) Confluence Park — flooding began at about 9,000 cfs at the upper end of the site, but substantial flooding did not occur until about 10,000 cfs; limited flooding began at the lower end of the site at 5,000–6,000 cfs (Irving and Burdick 1995; McAda and Fenton 1998); and (2) Johnson Slough — flooding began at 5,000–6,000 cfs in an old river oxbow, but substantial flooding did not occur until flows reached 8,000–10,000 cfs (McAda and Fenton 1998). Irving and Burdick (1995) estimated that there were about 99 ac of flooded habitat at Confluence Park, 156 ac at Johnson Slough, and 191 ac at Escalante SWA when the Gunnison River reached 14,800 cfs (at the USGS gage near Grand Junction). However, their data did not allow them to determine the relationship between discharge and flooded habitat.

Irving and Burdick (1995) identified 44 other sites in the Gunnison River that exhibited some potential for providing bottomland habitat. These 44 sites contained a total of about 383 ac of flooded habitat at 14,800 cfs (range, 0–48 ac). However, their analysis was not able to distinguish between quiet-water habitat and areas with fast water velocities. They estimated that about 3,200 ac of floodable habitat were available prior to flow regulation and dike construction.

Subsequent to Irving and Burdick's (1995) inventory, the floodplain at Escalante SWA received considerable attention. Cooper and Severn (1994a) sampled backwaters and other flooded habitats in the area to estimate primary and secondary productivity and document importance of floodplains to providing nutrients to the Gunnison River. They determined that floodability of the area had been substantially reduced by water development, but identified several options for dike removal that could increase flooded habitats under the current flow regime. Tetra Tech (2000) surveyed Escalante SWA and determined the relationship between discharge and flooded habitat (Figure 2.28) — flooded area was about 63 ac at 8,750 cfs

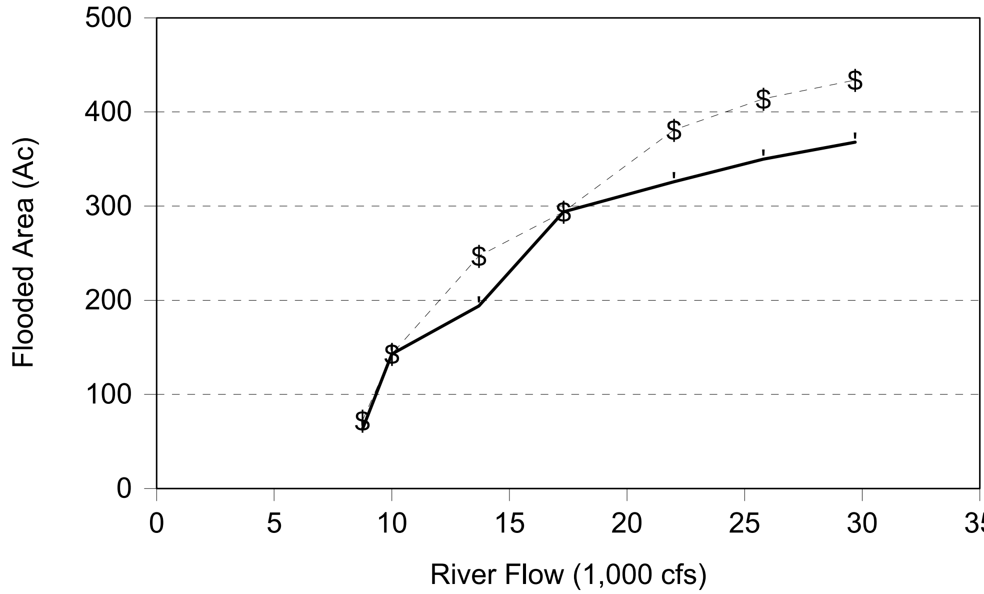

FIGURE 2.28. — Relationship of floodable area to river flow at Escalante SWA near Delta. Data from Tetra Tech (2000); dashed line indicates additional acreage that could be flooded by removing dikes or lowering banks. River flow was measured at the USGS gage near Grand Junction.

and increased to 368 ac at the extremely high flow of 29,700 cfs (water flow referenced to the USGS gage near Grand Junction). Flooded area could be increased at most flows by removing or breaching dikes at key locations along the river (Figure 2.28). McAda and Fenton (1998) also related available habitat to discharge at Escalante SWA, but included all available habitats rather than just floodplain habitat (Figure 2.29). Because of scheduling conflicts with Reclamation's helicopter, McAda and Fenton (1998) were unable to determine when flooding began in Escalante SWA, but their qualitative analysis indicated that floodplain habitat increased relatively little as flow increased from 13,300 to 15,800 cfs (the highest flows measured).

Based on the relationship developed by Tetra Tech (2000), the greatest relative gain in flooded habitat occurs as flows increase to 10,000 cfs. Increase in flooded habitat levels off between 10,000 and 13,700 cfs, and then increases again up to 17,300 cfs where it levels off for the remaining higher flows (Figure 2.28). Dike removal at a key location could keep habitat gain at a relatively high level as river flows increase to 17,000 cfs.

Water development has significantly reduced the frequency and duration of flows sufficient to connect the Gunnison River and its floodplain in Escalante SWA. Table 2.6 summarizes the significant reduction in frequency and duration of flooding at seven flows over the last 100 yr. As noted above, flows up to 10,000 cfs provided the greatest relative

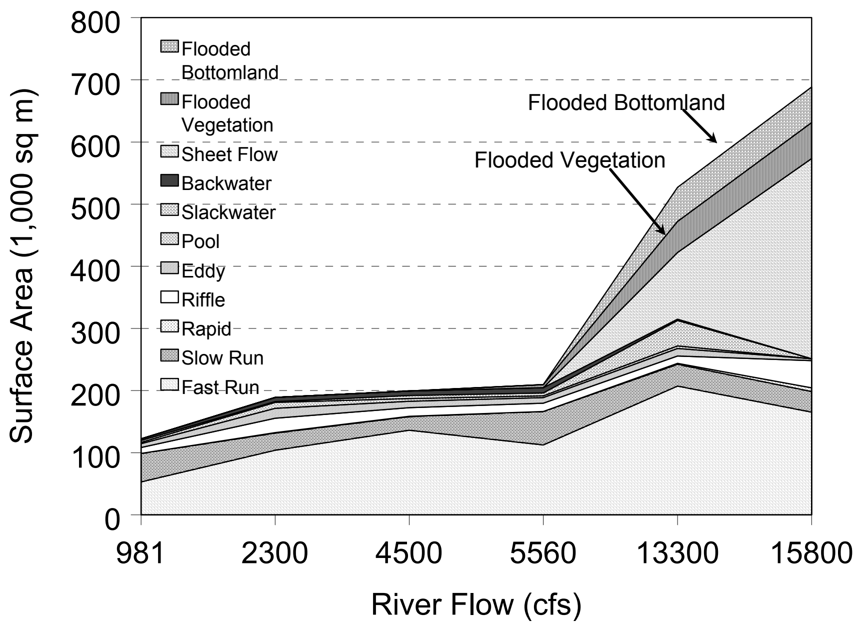

FIGURE 2.29. — Relationship of surface area of different habitat types to river flow at a study site within Escalante SWA. Modified from Figure 19 in McAda and Fenton (1998); study site is larger than used in Figure 2.28 and includes the main river channel. River flow was measured at the USGS gage near Grand Junction.

gain in flooded habitat. Spring flows of that level occurred 8 out of every 10 yr prior to construction of Taylor Park Reservoir, but currently occur in about 1 out of every 3 yr. Spring flows of that level lasted an average of 26 d early in this century, but average duration has declined to about 9 d under current conditions. The frequency and duration of higher flows have declined even further (Table 2.6). Cooper and Severn (1994a) summarized the effects of flow changes on the Gunnison River as follows:

> "Reduced flood frequency has a number of repercussions, including; (1) reduced floodplain dynamics resulting in fewer backwaters and oxbows being created and maintained, (2) fewer sites suitable for cottonwood regeneration, (3) reduced frequency of connection with existing backwaters and oxbows, (4) reduced flushing of floodplain soils to remove salts....
>
> The fact that neither May nor June flows retain their natural peak pre-dam condition is not encouraging. In fact these flows are very different. It indicates that floodplain dynamics are at a standstill, and the integration of native fishes into the floodplain will be possible on a very irregular basis, unless flows of greater than 12,000 can be restored."

TABLE 2.6. — Cumulative area of inundated floodplain habitat with increasing river discharge at Escalante SWA, and change in frequency and duration of inundation over three water-development periods.

Gunnison River Flows[a] (cfs)	Flooded Acreage	Average (range) number of days per year that flows were equaled or exceeded			Frequency of years that flows were equaled or exceeded		
		Pre Taylor[b]	Pre Aspinall[b]	Post Aspinall[b]	Pre Taylor[b]	Pre Aspinall[b]	Post Aspinall[b]
8,750	63 [9][c]	33.6 (0–62)	21.9 (0–66)	12.5 (0–71)	81%	68%	45%
10,000	143	25.5 (0–57)	17.1 (0–56)	8.8 (0–65)	81%	57%	33%
13,700	194 [53][c]	11.2 (0–38)	7.8 (0–39)	3.4 (0–32)	67%	43%	18%
17,300	294	5.6 (0–25)	2.7 (0–26)	0.8 (0–17)	48%	32%	12%
22,000	326 [55][c]	1.7 (0–15)	0.6 (0–9)	0.1 (0–2)	22%	14%	3%
25,800	350 [64][c]	0.7 (0–12)	0.2 (0–5)	0 -	11%	7%	0%
29,700	368 [66][c]	0.3 (0–6)	0 -	0 -	7%	0%	0%

[a] Measured at the USGS gage near Grand Junction (09152500).

[b] Pre-Taylor Park 1897–1899, 1902–1906, and 1917–1936; Pre-Aspinall Unit 1937–1964; Post-Aspinall Unit 1965– 1997.

[c] Brackets indicate additional acreage that could be inundated with bank lowering and dike removal.

Irving and Burdick (1995) identified more than 50 floodable bottomlands of various sizes along the Colorado River downstream from the mouth of the Gunnison River. They considered five sites located within the 18-mile reach to be high priority areas for floodplain restoration. Relatively little work to determine the floodability of these sites has been done; however, Pitlick and Cress (2000) estimated that bankfull discharge at or near these sites ranged from 32,000 to 48,000 cfs. No relationships between river stage and flooded habitat are available. These high priority sites include Walker SWA, which is heavily used by Colorado pikeminnow in spring (Sections 3.2.1 and 3.2.2) and was one of the last places where wild razorback suckers were found in the upper Colorado River (Section 3.3.1). Staff gage data indicate that usable quiet-water habitat occurs at the mouth of a large backwater there at flows of 16,000 cfs; however, most of the backwater remains shallow and unavailable to large fish at that stage (Scheer 1998).

Irving and Burdick (1995) also identified an important floodplain area near Moab at Scott Matheson WP. Cooper and Severn (1994b) assessed the floodability of Matheson WP and determined that flows of about 40,000 cfs (as measured at the USGS gage near Cisco) or greater are required for substantial flooding to occur. As with other sites in the subbasin, the frequency and duration of river flows that provide critical floodplain habitat at Matheson WP have declined. Cooper and Severn (1994b) concluded that flows of 40,000 cfs or greater occurred for 5 d or more in 1 out of 2 yr during 1914–1958, but the frequency declined to 1 in 9 yr during 1959–1993. Flow duration of 10 d or more occurred 1 out of 3 yr during the early period, but only 1 out of 11 yr during the second period. As with other floodplains in the upper subbasin, the contribution of Matheson WP to the productivity of the Colorado River has been substantially reduced because it is infrequently connected to the river under current conditions. Dike removal would increase floodplain habitat there, but specific relationships between river flow and area of inundation have not been described. The only juvenile razorback suckers collected from the Colorado River were found in the vicinity of Matheson WP (Section 3.3.1).

2.2.5 Influence of Water Development on River Temperature

The typical effects of deep-release dams (such as Blue Mesa) on water temperature of a river are dramatic decreases in summer temperatures and increased winter temperatures (e.g., Vanicek et al. 1970; Petts 1984). The hypolimnial releases of cold, clear water displace the rhithron-potamon transition zone downstream (summarized by Stanford 1994) and allow cold water species to occupy habitat formerly occupied by warm-water species (e.g., Vanicek et al. 1970). Water temperatures in the Gunnison River are currently 8–12°C immediately downstream from Crystal Reservoir (G. Smith, unpublished thermograph data) which has allowed reproducing rainbow trout and brown trout populations to replace the native fish community (Wiltzius1978).

The rhithron-potamon transition zone now occurs downstream from the confluence with the North Fork of the Gunnison River where water temperatures have been reduced by as much as 10°C in summer (summarized by Stanford 1994). However, the river warms rapidly after leaving the Black Canyon and Gunnison Gorge. McAda and Kaeding (1991a) used a temperature model to estimate that average water temperatures in the Gunnison River near Delta declined about 2°C after construction of the Aspinall Unit, but pre-dam temperatures are not available to validate the estimated decrease. The river continues to warm as it moves downstream, and it reaches estimated pre-dam water temperatures by the time it enters the Colorado River (McAda and Kaeding 1991a). Water temperatures in the Colorado River are unaffected by the Aspinall Unit.

Currently, summer water temperatures in the Gunnison River near Delta average about 2°C less than the lower portion of the river (Table 2.7). These average temperatures are about 3°C lower than river reaches in other parts of the upper basin that have relatively large

Colorado pikeminnow populations (Table 2.7). They are about 1°C warmer than the Green River in Brown's Park, which is occasionally occupied by small numbers of Colorado pikeminnow (Muth et al. 2000; C. Kitcheyan, personal communication). Although these temperature differences are small, minor differences may have important cumulative effects on metabolism and growth of fish (e.g., Weatherley 1972). Implications of temperature change in the Gunnison River on Colorado pikeminnow distribution are summarized in Section 3.2.4.

TABLE 2.7. — Average summer water temperature (°C) of the Gunnison River near Delta and near the mouth at Grand Junction. Water temperatures at other sites in the upper Colorado River basin occupied by Colorado pikeminnow are given for comparison. Data are averaged mean-monthly water temperatures for 1992, 1995, 1997, and 2000.[a]

Month	Gunnison River at Delta	Gunnison River at Grand Junction	Yampa River at Government Bridge, Colorado	Green River at Browns Park, Colorado	Green River at Jensen, Utah
Jun	14.3	15.5	14.7	14.1	17.0
Jul	16.5	18.4	19.2	16.1	20.0
Aug	17.8	20.2	20.4	16.2	20.8
Sep	15.6	17.3	16.0	14.1	16.8

[a] The only years when complete data sets were available for all five sites. Available data for 1992–2000 are provided in Table A.27. Data were compiled from thermographs maintained by the Recovery Program (G. Smith, unpublished data).

3.0 FISHES OF THE COLORADO AND GUNNISON RIVERS

The Colorado River basin originally supported a depauperate fish fauna with 36 species from 20 genera and 9 families (summarized by Carlson and Muth 1989). Of these 36 native species, 64% were endemic to the basin and only eight were found in both the upper and lower portions of the basin (Carlson and Muth 1989). Because of widespread introductions, more than 100 fish species are now found in the basin (Carlson and Muth 1989). Tyus et al. (1982) documented 13 native and 42 nonnative fishes that have been reported from the Colorado River and its tributaries upstream from Lake Powell in recent years; they also noted 10 hybrid forms. Four fishes native to the large rivers of the upper basin — razorback sucker, Colorado pikeminnow, humpback chub, and bonytail — are listed as endangered under ESA (USFWS 2000).

This chapter describes the fish community of the mainstem rivers of the upper Colorado River subbasin. The first section provides an overview of the fish community with general information on distribution and abundance of the most common species found in the system. The remaining four sections provide basic information on distribution, abundance, habitat requirements, and life history of razorback sucker, Colorado pikeminnow, humpback chub, and bonytail that is pertinent to making flow recommendations for the Gunnison and Colorado rivers. These sections are of varying length because the body of knowledge varies greatly for the four species. Colorado pikeminnow is widespread and has been the subject of many studies throughout the basin and there is considerable information on its life history and ecology. In contrast, bonytail is so rare in the upper basin that it is functionally extinct and very little life-history information is available. Ecological and life-history information for humpback chub and razorback sucker are available, but not to the extent of Colorado pikeminnow. The following sections emphasize information from the Colorado and Gunnison rivers, but data from the Green and San Juan basins and the lower Colorado River basin are also presented.

This chapter is not intended to be an exhaustive literature review of the four endangered species, but rather an overview of the known information that is pertinent to developing flow recommendations for the Gunnison and Colorado rivers. Literature reviews of the life history and ecology of these species are available in Bestgen (1990), Minckley et al. (1991), Tyus (1991a), Holden (1999) and Muth et al. (2000). Life-history summaries for other common members of the Colorado River fish community are provided in Valdez (1990), Muth and Nesler (1993), Lentsch et al. (1996), and Holden (1999). These references and material cited below should be consulted if more detailed information is desired.

3.1 FISH COMMUNITY

3.1.1 Native Species

A total of six other native fishes inhabit portions of the Colorado and Gunnison rivers that have been designated as critical habitat for the four endangered fishes (i.e., Gunnison River upstream to Uncompahgre River; Colorado River upstream to Rifle; Table 3.1). Two of those species — mountain whitefish[4] and mottled sculpin — are generally found only in the uppermost reaches of the rivers inhabited by the endangered fishes, in the transition between warm- and cold-water habitats. These species generally do not overlap with the endangered fishes except at the most downstream limits of their distribution. The other four species — flannelmouth sucker, bluehead sucker, roundtail chub, and speckled dace — coexist with the endangered fishes throughout their range.

Flannelmouth sucker, bluehead sucker, roundtail chub, and speckled dace are generally common to abundant throughout the Gunnison River (Valdez et al. 1982a; Burdick 1995) and the Colorado River upstream from Westwater Canyon (Valdez et al. 1982b; Osmundson 1999); however, their relative abundance decreases in downstream reaches of the Colorado River (Valdez et al. 1982b; Osmundson 1999) where river gradient diminishes and substrate size decreases (Pitlick and Cress 2000; see Section 2.2.1). This decrease in relative abundance is especially dramatic for roundtail chub, which is rarely collected from the Colorado River downstream from Westwater Canyon (T. Chart, personal communication; Osmundson 1999).

Osmundson (1999) divided the Colorado River into 11 strata based on major geomorphic changes along the river. He also included one stratum in the Gunnison River. Each stratum was electrofished along both shorelines in autumn and spring for 2 yr. Figure 3.1 depicts mean catch rates for bluehead sucker, flannelmouth sucker, roundtail chub and speckled dace for the 2-yr study and dramatically shows the decline in relative abundance of all fishes in the Colorado River downstream from Westwater Canyon. Bluehead sucker and flannelmouth sucker comprised the majority of fish captured in all strata, except for the lowermost stratum of the Colorado River. Catch rates in the Gunnison River stratum are equivalent to the highest observed in the Colorado River.

3.1.2 Nonnative Species

Twenty-four nonnative species have been collected from the Gunnison and Colorado rivers in reaches that are currently occupied by one or more of the endangered fishes (Table 3.2). Some of these species are represented by a few individuals, but others have become widespread and abundant. The most abundant of nonnative fishes are common carp, fathead minnow, sand shiner, and red shiner. All are widely distributed throughout the subbasin and numerically comprise a substantial portion of the fish fauna in most reaches. Channel catfish are abundant and wide spread in the Colorado River, but extremely rare in the Gunnison River where Burdick (1995) captured only one channel catfish in 2 yr of intensive sampling. That fish was large and believed to be a survivor of fish stocked by CDOW in the 1960s. The species is apparently unable to recruit successfully in the Gunnison River and has not established a self-sustaining population there. White suckers are abundant in upper reaches of

[4] Scientific names of fish mentioned in this chapter are provided in Tables 3.1 and 3.2.

TABLE 3.1. — Native fishes of the Gunnison and upper Colorado rivers.

Family/Scientific Name	Common Name	Distribution and Abundance in the Colorado and Gunnison Rivers[a]
Catostomidae		
Catostomus discobolus	bluehead sucker	Widespread, common to abundant.
C. latipinnis	flannelmouth sucker	Widespread, common to abundant.
Xyrauchen texanus	razorback sucker	Endangered; incidental.
Cyprinidae		
Gila cypha	humpback chub	Endangered; locally common in Black Rocks and Westwater Canyon; incidental in Gunnison River.
G. robusta	roundtail chub	Abundant in Gunnison and upper Colorado River; rare in lower Colorado River.
G. elegans	bonytail	Endangered; incidental in Colorado River.
Rhinichthys osculus	speckled dace	Common and widespread, but specific to areas with rocky substrate.
Ptychocheilus lucius	Colorado pikeminnow	Endangered; widespread, but rare in Colorado River; incidental in Gunnison River.
Cottidae		
Cottus bairdi	mottled sculpin	Rare to common in cool water reaches of the two rivers.
Salmonidae		
Oncorhynchus clarki pleuriticus	Colorado River cutthroat trout	Rare, mostly in remnant populations in isolated, high-elevation tributaries.
Prosopium williamsoni	mountain whitefish	Common in cool/cold water reaches of the Colorado River.

[a] Abundant = occurring in large numbers and consistently collected in a designated area; Common = occurring in moderate numbers and frequently collected in a designated area; rare = occurring in very low numbers or having a sporadic distribution over a large area; incidental = occurring in very low numbers and known from only a few collections. Primary sources for information: Valdez et al. (1982a, 1982b); Valdez (1990); McAda et al. (1994a, 1994b, 1995, 1996, 1997 and 1998); Burdick (1995); Osmundson (1999); Trammell and Chart (1999b).

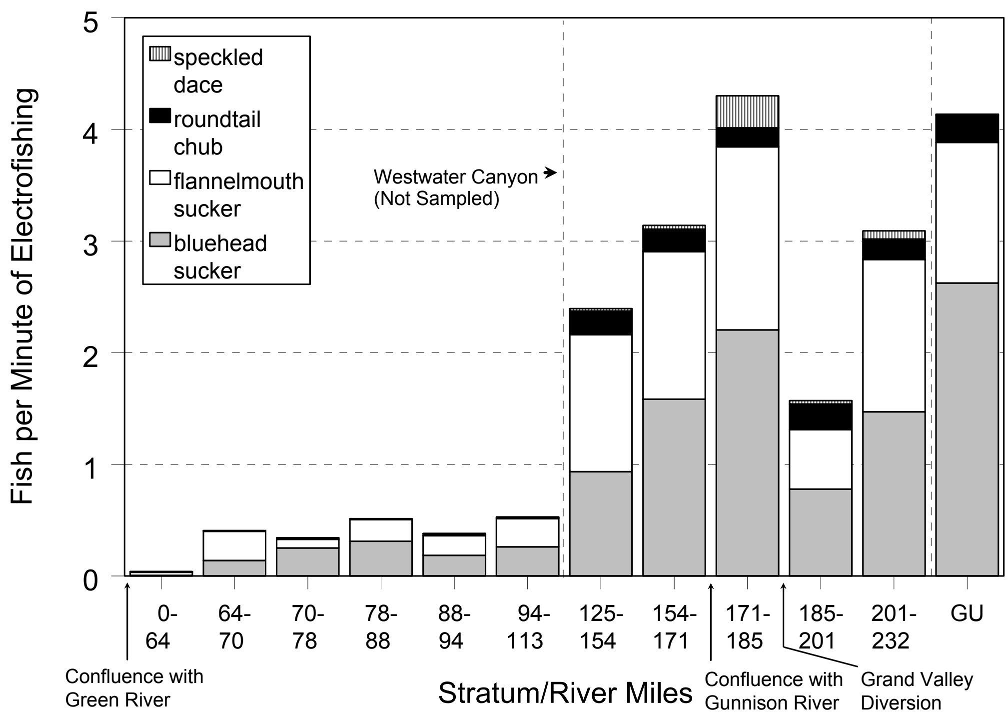

FIGURE 3.1. — Mean electrofishing catch rates (fish captured per minute of shoreline electrofishing) for four native fishes (bluehead sucker, flannelmouth sucker, roundtail chub, and speckled dace) in 11 strata of the Colorado River and 1 stratum of the Gunnison River (GU; RM 29.8–41.6). Data were excerpted from Figure 2 in Osmundson (1999).

of both rivers and are expanding downstream (Burdick 1995; Osmundson 1999). Their hybrids with bluehead sucker and flannelmouth sucker are becoming common (Burdick 1995).

The three small-bodied cyprinids — fathead minnow, sand shiner, and red shiner — are abundant in backwaters and other low-velocity habitats in both the Gunnison and Colorado rivers. These three species comprise 80–100% of the fish found in Colorado river backwaters (usually >95%; McAda et al. 1994b; Trammell and Chart 1999b) and 21–85 % of the fish found in Gunnison River backwaters (Burdick 1995). These quiet-water habitats are also occupied by young of most native species for at least a portion of their first summer of life (McAda et al. 1994b; Trammell and Chart 1999b, 1999c). Backwaters are important habitat for age-0 Colorado pikeminnow (Tyus and Haines 1991; Section 3.2.2), and the introduced cyprinids negatively interact with young Colorado pikeminnow in a variety of ways including competition (Beyers et al. 1994), agonistic behavior (Karp and Tyus 1990b), and predation (Bestgen et al. 1997).

TABLE 3.2. — Nonnative fishes of the Gunnison and upper Colorado rivers that overlap in distribution with the four endangered fishes.

Family/Scientific Name	Common Name	Distribution and Abundance in the Colorado and Gunnison Rivers[a]
Catostomidae		
C. commersoni	white sucker	Common to abundant in upper Gunnison River, becoming more common in other areas.
C. catostomus	longnose sucker	Locally common in upper Gunnison River.
C. discobolus x *C. commersoni*	white x bluehead	Locally common, especially in Gunnison River.
C. latipinnis x *C. commersoni*	white x flannelmouth	Locally common, especially in Gunnison River.
C. latipinnis x *X. texanus*	flannelmouth x razorback	Rare to incidental.
C. latipinnis x *C. discobolus*	flannelmouth x bluehead	Rare.
Cyprinidae		
Cyprinus carpio	common carp	Widespread and abundant.
Cyprinella lutrensis	red shiner	Widespread and abundant, especially in low velocity habitats.
Notropis stramineus	sand shiner	Widespread and abundant, especially in low velocity habitats.
Pimephales promelas	fathead minnow	Widespread and abundant, especially in low velocity habitats.
Hybognathus hankinsoni	brassy minnow	Incidental in Colorado River.
Ctenopharyngodon idella	grass carp	Incidental in Colorado River.
G. atraria	Utah chub	Incidental in Colorado River.
Centrarchidae		
Lepomis cyanellus	green sunfish	Abundant in river-side ponds; locally common to abundant in some areas of both rivers.
Lepomis machrochirus	bluegill	Locally common in river-side ponds; incidental in both rivers.

TABLE 3.2. — Continued.

Family/Scientific Name	Common Name	Distribution and Abundance in the Colorado and Gunnison Rivers[a]
Centrarchidae (Continued)		
Micropterus salmoides	largemouth bass	Locally common in river-side ponds; locally common in backwaters of the Colorado River near ponds.
M. dolomieui	smallmouth bass	Incidental in ponds and river.
Pomoxis nigromaculatus	black crappie	Locally common in river-side ponds; incidental in Colorado River.
Ictaluridae		
Ameiurus melas	black bullhead	Abundant in river-side ponds; locally common in river reaches adjacent to ponds.
Ictalurus punctatus	channel catfish	Widespread and common to abundant in the Colorado River downstream from diversion dams. Incidental in the Gunnison River above Redlands Diversion.
Esocidae		
Esox lucius	northern pike	Incidental in most reaches of the two rivers. Rare in the Gunnison River near Delta.
Percidae		
Stizostedion vitreum	walleye	Incidental in the lower Colorado River.
Serranidae		
Morone saxatilis	striped bass	Incidental in the lower Colorado River.
Cyprinodontidae		
Fundulus kansae	plains killifish	Locally common to abundant in ponds; rare to locally common in river backwaters.

TABLE 3.2. — Continued.

Family/Scientific Name	Common Name	Distribution and Abundance in the Colorado and Gunnison Rivers[a]
Poeciliidae		
Gambusia affinis	western mosquitofish	Locally common to abundant in ponds; rare to locally common in river backwaters.
Salmonidae		
Salmo trutta	brown trout	Common to abundant in cool/cold water reaches of the Gunnison and Colorado Rivers.
Oncorhynchus mykiss	rainbow trout	Common to abundant in cool/cold water reaches of the Gunnison and Colorado Rivers.

[a] Abundant = occurring in large numbers and consistently collected in a designated area; Common = occurring in moderate numbers and frequently collected in a designated area; rare = occurring in very low numbers or having a sporadic distribution over a large area; incidental = occurring in very low numbers and known from only a few collections. Primary sources for information: Valdez et al. (1982a, 1982b); Valdez (1990); McAda et al. (1994a, 1994b, 1995, 1996, 1997 and 1998); Burdick (1995, 2002a); Trammell and Chart (1999b);Osmundson (2000a).

Several nonnative centrarchids have become established in river-side ponds along both rivers and often escape to riverine backwaters where they prey on native fishes. Green sunfish are abundant in ponds and irrigation drains that have access to the river during high water (Burdick et al. 1997; Burdick 2002a) and are routinely found in backwaters of both rivers (McAda et al. 1994b). Largemouth bass are common in riverside ponds (Burdick et al. 1997) and are also commonly found in backwaters (McAda et al. 1994b), sometimes in high numbers (Osmundson 2000a). Bluegill and black crappie occur in some ponds (Burdick et al. 1997) and are periodically collected from the river (McAda et al. 1994b). Several species other than centrarchids — black bullhead, western mosquitofish, and plains killifish — are also abundant in riverside ponds (Burdick et al. 1997; Burdick 2002a) and can be locally common in nearby riverine habitats (McAda et al. 1994b).

Salmonids are established in the tailwater downstream from Crystal Reservoir. Originally stocked into the system, rainbow trout and brown trout have developed self-sustaining populations in the cold, hypolimnial releases from Blue Mesa Reservoir (Wiltzius 1978; Section 2.2.3). The center of their distribution is upstream from the confluence with the North Fork of the Gunnison River, but large numbers of both species are found in the

Gunnison River as far downstream as Delta (Burdick 1995). Trout do not overlap with the endangered species to a large degree because of their preferences for cooler water, but they are occasionally captured downstream from Delta, (Burdick 1995) and in the Colorado River downstream from Rifle (Osmundson 1999).

Northern pike were consistently collected in low numbers from the Gunnison River upstream from Delta (Burdick 1995). The species was introduced into Paonia Reservoir on a tributary to the North Fork of the Gunnison River and some individuals escaped from the reproducing population that became established there (S. Hebein, personal communication). This small population was recently reduced with a trial mechanical removal program (McAda 1997). The species was recently illegally introduced into Crawford Reservoir on the Smith Fork of the Gunnison River (S. Hebein, personal communication). Northern pike are collected infrequently in other parts of the Colorado and Gunnison rivers. The remaining species listed in Table 3.2 are rare in the Gunnison and Colorado rivers and are represented by few individuals (Recovery Program database, unpublished data).

As noted in Chapter 1, interaction with nonnative fishes is one of several factors that have contributed to the decline of the four endangered fishes. The Recovery Program has initiated a series of management activities to control abundance and distribution of nonnative fishes (Lentsch et al. 1996; Tyus and Saunders 1996), including: (1) restricting species and locations for future introductions; (2) liberalizing harvest regulations; (3) preventing escapement from existing sources; (4) chemical or mechanical removal; and (5) preventing upstream movement into unoccupied habitat. These options are covered elsewhere and fall outside the scope of this document. However, one option to control introduced fishes — flow management — is appropriate to this report. Altered flow regimes are thought to have assisted some of the introduced species to increase their abundance and range in the Colorado River basin (Behnke and Benson 1983), and there is evidence that high spring flows decrease some species' abundance, at least temporarily (summarized by Lentsch et al. 1996).

3.1.3. Influence of River Flow on Non-Endangered Fishes in the Colorado and Gunnison Rivers.

McAda and Ryel (1999) compared relative density of six non-endangered species (three native and three nonnative) that were commonly collected in backwaters and other low-velocity habitats in summer and autumn in two reaches of the Colorado River. Their study was conducted during 1982–1996 when peak spring flows in the Colorado River ranged from 9,670 to 69,500 cfs (measured at the USGS gage near Cisco). Backwaters provide important habitat for young-of-the-year (YOY) Colorado pikeminnow (Section 3.2.2). The three nonnative fishes — fathead minnow, red shiner, and sand shiner — were abundant and usually comprised the majority of fish collected in all samples (McAda and Ryel 1999) and are believed to compete with and prey on small Colorado pikeminnow (Beyers et al 1994; Bestgen et al. 1997). These species are small-bodied fishes that rarely exceed 70 mm long as adults, and all age classes are present in autumn backwater samples. The three native species — bluehead sucker, roundtail chub, and flannelmouth sucker — attain much larger sizes as adults and fish captured by seining were primarily YOY. Therefore, autumn density (measured as catch-per-unit-effort [CPE]) of nonnative species in backwaters represented total population size of the nonnative species, whereas density of the three native species represented a measure of annual reproductive success. Summer larval samples represented annual reproductive success for all species.

Table 3.3 summarizes relationships between relative density of larval fish and average high flow (average of 15 d before and after the highest mean-daily flow of the year) during spring runoff. Flannelmouth suckers were the only native fish to exhibit a significant relationship with spring flow, but Pearson correlation coefficients for all native species were positive. In contrast, all three nonnative species had significant negative relationships between spring runoff and larval density in two study reaches (McAda and Ryel 1999).

Relative density in autumn followed the same patterns exhibited by larval fish in summer (Table 3.4). Relative density of YOY flannelmouth sucker and bluehead sucker exhibited significant positive relationships with spring runoff in at least one of the study reaches. Pearson correlation coefficients for all three native species were positive in both study reaches. Correlation coefficients for the three nonnative species were negative in both reaches and significantly so in all cases (Table 3.4).

TABLE 3.3. — Pearson correlation coefficients between mean number of larvae collected per sample and average high flow in spring, Colorado River, 1983–1985 and 1988–1994. Spring peak flows ranged from 9,670 to 69,500 cfs. Table 1 in McAda and Ryel (1999).

	Reach	
Species	1 (RM 0–110)	2 (RM 128–171)
Native		
bluehead sucker	0.01	0.36
Gila spp.	0.11	0.42
flannelmouth sucker	**0.68**[a]	0.35
speckled dace	0.03	0.07
Nonnative		
fathead minnow	**-0.62**[b]	**-0.59**[b]
red shiner	**-0.70**[a]	**-0.70**[a]
sand shiner	**-0.64**[a]	**-0.63**[a]

[a] Significant at $P<0.05$
[b] Significant at $P<0.1$

TABLE 3.4. — Pearson correlation coefficients between geometric-mean CPE of six species collected by seining Colorado River backwaters in autumn and average high flow in spring, 1983–1996. Spring peak flows ranged from 9,670 to 69,500 cfs. Significant correlations are in bold. Table 5 in McAda and Ryel (1999).

	Reach	
Species	1 (RM 0–110)	2 (RM 128–171)
Native[c]		
roundtail chub	0.27	0.10
flannelmouth sucker	**0.68**[a]	0.01
bluehead sucker	**0.49**[b]	0.21
Nonnative[c]		
fathead minnow	**-0.67**[a]	**-0.74**[a]
red shiner	**-0.61**[a]	**-0.52**[b]
sand shiner	**-0.50**[b]	**-0.57**[a]

[a] Significant at $P<0.05$
[b] Significant at $P<0.1$
[c] YOY only for native fishes, all age classes for nonnative fishes.

McAda and Ryel (1999) used correlation analysis to compare a variety of variables describing river flow over the course of the year with relative density of fish in autumn backwaters. Relative density of sand shiner was not significantly correlated with any flow variables, but red shiner and fathead minnow had significant negative correlations with variables describing peak flow (average high flow [ave-high; mean of mean-daily flow for 15 d on either side of the highest flow of the year] and peak flow on the highest day of the year [high]), mean-monthly flow for spring and summer months, and the number of days that the Colorado River stayed above flows ranging from 5,000 to 25,000 cfs (5K–25K; Table 3.5). They did not do individual comparisons for native species, but combined catch rates for flannelmouth sucker, bluehead sucker, and roundtail chub were positively correlated with the same variables (Table 3.5). Because all of the flow variables are closely related (e.g., years with high spring flows tend to have high summer and autumn flows; McAda and Ryel 1999), it is hard to determine which season's flows were most important in determining species abundance. It is likely that flows during all parts of the year are important, but peak flows in spring are the dominating influence for the year (see below).

McAda and Ryel (1999) also used principal components analysis to identify years with similar flow regimes, including flows in the year preceding fish collection (Figure 3.2). Two

TABLE 3.5.—Flow variables[a] that were significantly correlated (Pearson correlation coefficient; *P*<0.05) with autumn CPE of red shiner, sand shiner (no significant correlations), fathead minnow, and native species other than Colorado pikeminnow (combined). Negative correlations are indicated by '-', positive correlations are indicated by "+". Excerpted from Table 8 in McAda and Ryel (1999).

Red Shiner	Fathead Minnow	Sand Shiner	Native Fishes
High -	High -		High +
Ave-high -	Ave-high -		Ave-high +
May -	April -		April +
June -	May -		May +
July -	June -		September +
August -	July -		5K +
September -	August -		10K +
5K -	September-		15K +
10K -	5K -		20K +
15K -	10K -		25K +
20K -	15K -		
25K -	20K -		
	25K -		

[a] Range of flow variables is given in Table A.28.

significant factors were found — the most important variables in factor 1 described flows in the given year, whereas factor 2 primarily consisted of the previous year's flows with a lesser, but opposite effect of present year flows. When the 7 yr with highest combined catch rates for red shiner, sand shiner, and fathead minnow were plotted on the same graph they grouped together and were related to peak flows less than 30,000 cfs in the year of sampling (measured at the USGS gage near Cisco; 5 out of 6 yr were less than 20,000 cfs). Years with low combined CPE were associated with peak flows that exceeded 30,000 cfs in the year of sampling (5 out of 6 yr were greater than 40,000 cfs; Figure 3.2).

Larval drift was monitored in the Gunnison and upper Colorado rivers by Anderson (1999) and in the lower Colorado River by Trammell and Chart (1999a) during 1992–1996. Anderson (1999) reported a significant positive relationship between drift of native fish and spring runoff that was primarily driven by very high density in the high-water year of 1995 and very low density in the low-water years. Intervening years were variable. A significant linear correlation was not observed in the lower river, but native species were most abundant

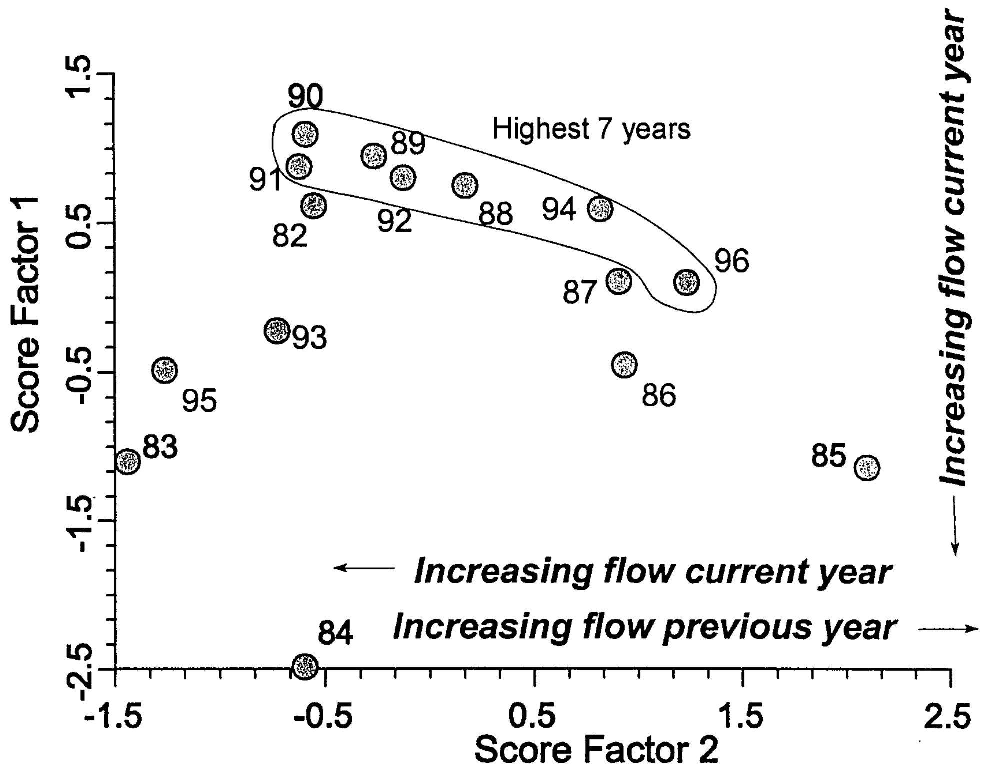

FIGURE 3.2. — **Plot of scores for factors 1 and 2 determined by principal components analysis of 13 river flow variables compared with relative density of three introduced cyprinids. The year of each case is indicated. The circled points refer to the 7 highest years of combined catch rates for red shiner, sand shiner, and fathead minnow. Figure 5 in McAda and Ryel (1999). Factor loadings of flow variables are in Table A.29.**

in samples taken during the high-water years of 1993 and 1995 (Trammell and Chart 1999a). Significant linear relationships also were not found between the three nonnative cyprinids and spring runoff, but they were extremely abundant in the drift during the low-water year of 1994 and their relative density was reduced in the high-water years of 1993 and 1995.

Based on these studies, two generalizations can be made about the effect of runoff on the Colorado River fish community: (1) relative density of the three introduced species was reduced by moderate to high spring runoff, and (2) relative density of young of native species was enhanced (or, at minimum, not negatively affected) by moderate to high spring runoff. This was a consistent pattern that applied to both larval and YOY fish (as well as adults of the introduced species) in both study areas of the Colorado River. In addition, Burdick (1995) found that young of native fish composed a much larger portion of fish assemblages in Gunnison River backwaters in the high-water year of 1993 than they had in the low water year of 1992. This is consistent with the patterns detected by McAda and Ryel (1999), but a 2-yr data set is not sufficient to determine trends.

Similar relationships between fish density and river flow have been documented in several reaches of rivers in the upper Colorado River basin including (1) high-gradient, canyon-bound reaches such as lower Yampa Canyon (Muth and Nesler 1993) and the Colorado River in Westwater Canyon (Chart and Lentsch 1999a), (2) moderate gradient, cobble-substrate floodplain areas such as the Colorado River in the Grand Valley (Osmundson and Kaeding 1989a; McAda and Ryel 1999) or side channels in the San Juan River (Gido et al. 1997), and (3) low-gradient reaches with silt-sand substrates like the lower Colorado River downstream from Moab (Valdez 1990; Trammell and Chart 1999b; McAda and Ryel 1999). With the exception of Gido et al. (1997), these studies utilized data covering periods of at least 5 yr. There was some variation in results and the relationships were not significant for every species in every river reach, but the generalization that relative density of the three introduced cyprinids was reduced following high spring runoff and relative density of native species was increased (or at least not negatively affected) following high spring runoff was consistent among all the different studies.

These studies show that moderate to high spring runoff (>30,000 cfs), and summer conditions resulting from high runoff, reduced the abundance of the three nonnative cyprinids. Causal mechanisms may include flushing adults downstream, reducing their ability to successfully reproduce (by delaying spawning or reducing hatching success because of continued high flows and cool water temperatures), or a combination of the two. The introduced species appear less able to cope with high flows than native species. When the river rises high enough to eliminate low-velocity habitats, they may be unable to maintain their position and are flushed downstream. The ability to withstand high flushing flows has been hypothesized as being important to persistence of native fishes in southwestern streams in the face of intense competition and predation from introduced species (Meffe 1984; Minckley and Meffe 1987). However, the difference between mean annual flows and runoff flows described for small southwestern streams is much greater than occurs in the mainstem rivers of the upper basin. Most examples presented by Minckley and Meffe (1987) included floods that ranged from 30 to 360 times the mean annual flow of the streams and rivers discussed. One extreme example included a flood 2,000 times the mean annual flow of the stream monitored. In contrast, peak flows in mainstem rivers of the upper basin are 10 to 15 times mean annual river flow.

Density of the three nonnative cyprinids is especially great after two or more consecutive years of low runoff, which allows rapid increase in population size. These species are fractional spawners (i.e., females can produce more than one clutch of eggs; Muth and Nesler 1993), and warm temperatures and low flows allow repeated spawning by adults. Although population reductions caused by high spring flows are temporary, the short-term reduction in predators and competitors may allow increased survival of YOY Colorado pikeminnow in years when standing crops of nonnative fishes are reduced.

3.2 COLORADO PIKEMINNOW

Colorado pikeminnow (formerly Colorado squawfish, Nelson et al. 1998) is a large piscivorous cyprinid endemic to the Colorado River basin (Minckley 1973) and is one of four large cyprinids of the genus *Ptychocheilus* native to the western United States (Robins et al. 1991). Colorado pikeminnow is the largest of the four and reportedly reached lengths approaching 1.8 m and weights of 45 kg (Minckley 1973) during European settlement of the west. The largest Colorado pikeminnow captured in recent years was 1,240 mm long and exceeded the capacity of the scale used by the Service biologists who captured it (T. Modde, personal communication). In addition to that specimen, only 7 of more than 5,000 Colorado pikeminnow captured from the upper Colorado River basin since the mid 1970s have been 900 mm or longer (Recovery Program database, unpublished data). Those seven fish ranged from 901 to 960 mm in length and weighed between 5 and 8.2 kg. Colorado pikeminnow this large may be 45–55 yr old (Osmundson et al. 1997a).

The species was once widespread in the large rivers of the Colorado River basin, but it was eliminated from the basin downstream from Lake Powell by the late 1960s (Minckley 1973). Although it still exists in the upper basin, its range has been reduced by construction of large reservoirs that eliminated habitat and changed downstream water quality (e.g., Vanicek et al. 1970) and construction of instream barriers that blocked access to historic range (Burdick and Kaeding 1990). The loss of habitat in the lower basin, unknown status of the species in the upper basin, and potential for further habitat loss through construction of more reservoirs prompted the species to be included as endangered when the first list of endangered species was published in 1967 (USFWS 1967).

3.2.1 Distribution and Abundance

***General.* —** Colorado pikeminnow are currently found only in the upper Colorado River basin, including the Green, Colorado, and San Juan rivers and their larger tributaries. The largest population occurs in the Green River basin, including parts of the Yampa, White, Duchesne, and Price rivers (Tyus 1991a). Tyus (1991a) used several methods to approximate the abundance of adults in the Green River; these estimates ranged from 800 to 44,000 individuals, with an overall mean of 8,000. Increased catch rates for shoreline electrofishing conducted as a part of ISMP since 1986 (McAda 2002a) suggest that the Green River population has increased since Tyus's estimate, but there has been no attempt to quantify that increase. Recently, ISMP was expanded to include regular mark-recapture population estimates in the Green River basin, but the first estimate has not been made. Larvae and age-0 juveniles are found in the Green River every year (Tyus and Haines 1991), and subadults regularly recruit to the adult population (McAda 2002a).

The smallest Colorado pikeminnow population occurs in the San Juan River upstream from Lake Powell, where Platania et al. (1991) captured a total of eight adults between Lake Powell and Shiprock, New Mexico during a 2-yr (1987–1989) survey of the river. More recently, Ryden (2000a) captured 19 individual subadult and adult Colorado pikeminnow from the same reach of river during intensive electrofishing collections from 1991 to 1997.

Evidence of successful reproduction was found in the San Juan River, but larvae and age-0 juveniles were found infrequently and in very low numbers (Holden and Masslich 1997). Hatchery-produced age-0 Colorado pikeminnow were stocked annually from 1994 to 2000 (Archer et al. 2000). Stocked fish have been recaptured from 1 to 6 yr after their original release (Archer et al. 2000; Ryden 2000a).

Colorado River. — Colorado pikeminnow are distributed throughout the Colorado River from Price Stubb Dam, an impassible barrier at the upper end of the Grand Valley (RM 188.3), downstream to Lake Powell (Figure 3.3; Osmundson and Burnham 1998). The Recovery Program is scheduled to provide passage at the structure, but it currently remains an obstacle to fish movement.

Although Colorado pikeminnow use the entire river, there are distinct differences in distribution among age classes. In general, most adults are found in the upper reaches of the river and most subadults, juveniles, and YOY are found in the lower reaches (Valdez et al. 1982a; Archer et al. 1985; McAda and Kaeding 1991b; Osmundson et al. 1997b). This corresponds to the general distribution of different age classes in the Green River as well (Tyus 1991a). Osmundson and Burnham (1998) conducted an intensive river-wide study using mark-recapture to estimate the population size of subadult (250–500 mm long) and adult Colorado pikeminnow (>500 mm long) in the Colorado River. They divided the river into two subreaches — Westwater Canyon to Price Stubb Dam (RM 125–188) and confluence with Green River to Westwater Canyon (RM 0–113; Westwater Canyon itself was not sampled). They estimated that the average population size in 1991–1994 was 253 (95% CI, 161–440) for the upper reach and 344 (95% CI, 196–604) for the lower reach. They noted that almost all fish captured in the upper reach were adults (i.e. >500 mm), whereas most fish captured from the lower reach were subadults. Figure 3.4 presents the average length of fish captured in different subreaches of the Colorado River and depicts the trend toward smaller average size in downstream reaches of the river.

Although most adults were captured from the upper river, they were not distributed equally throughout the reach. Catch rates in two segments of the upper reach — known as the 18-mile reach (RM 154–171) and the 15-mile reach (RM 171–185) — were five to six times higher than in the lower third of the reach (Osmundson 2000; Figure 3.5). These reaches contain 8 to 10 times more adult Colorado pikeminnow per mi than the lower 100 mi of the Colorado River (Figure 3.5).

Osmundson (2002a) repeated the population estimate for the 1998–2000 period using the same techniques used by Osmundson and Burnham (1998). He also revised the previous estimate using length criteria for adults corresponding to recovery goals established in 2002 (USFWS 2002b; ≥450 mm total length [TL]) and provided a river-wide estimate. Average population size for the Colorado River was 503 adult Colorado pikeminnow for 1992–1994 and 604 for 1998–2000 (Osmundson 2002a). Although the average point estimate increased

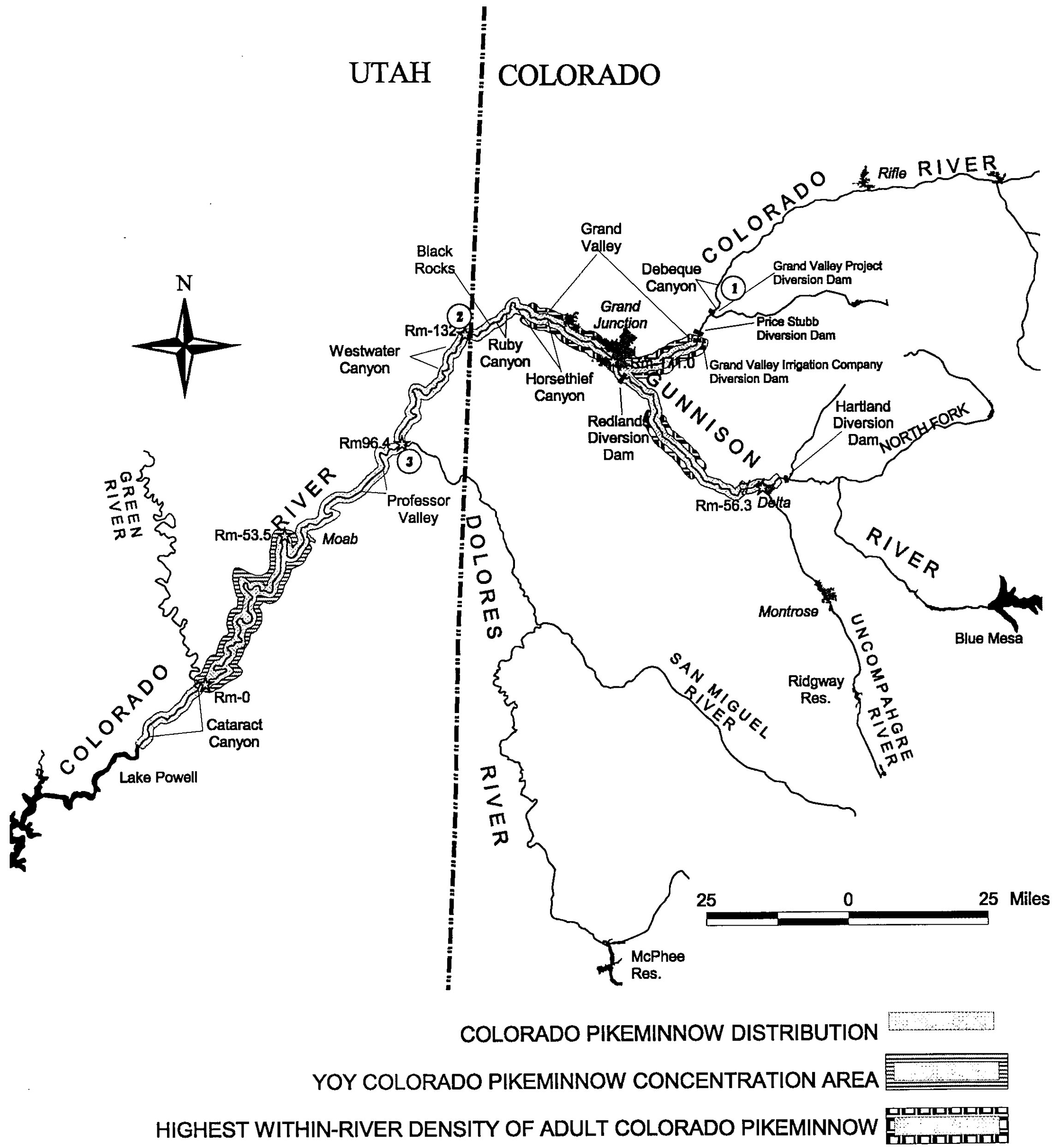

FIGURE 3.3. — Distribution of Colorado pikeminnow in the upper Colorado and Gunnison rivers.

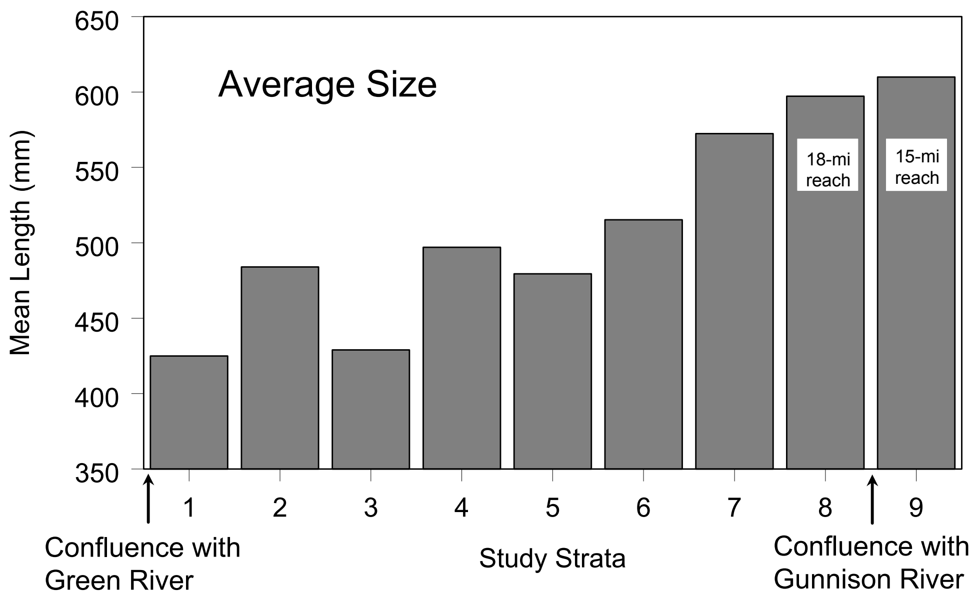

FIGURE 3.4. — Mean size of subadult and adult Colorado pikeminnow in the Colorado River for nine geomorphic strata described by Osmundson (1999). Figure 5 in Osmundson (2000).

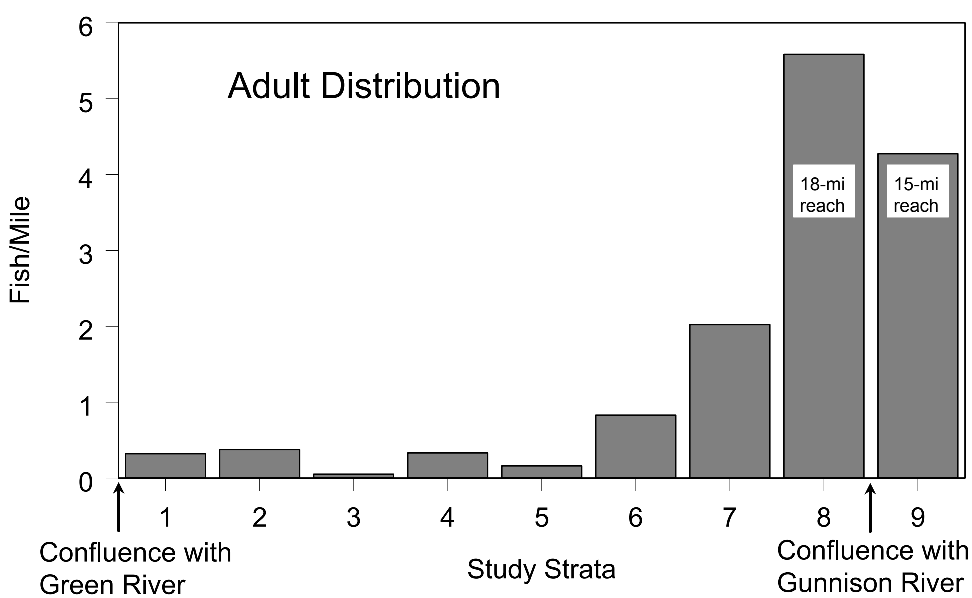

FIGURE 3.5. — Relative distribution of adult Colorado pikeminnow (defined as fish > 550 mm TL) in the Colorado River. Catch rates (fish per mi) were averaged across sampling passes for each year and those values were averaged for 6 yr of data (1991–1994 and 1998–1999). Strata correspond to geomorphic river reaches described by Osmundson (1999). Figure 4 in Osmundson (2000).

for the second period, the difference was not significant because of wide confidence intervals. An increase in the adult population during the 1990s was also suggested by an increasing catch rate in during spring ISMP electrofishing (Figure 3.6; McAda 2002a). However, electrofishing catch rates dropped off in 1999 and 2000, whereas population estimates did not.

Density and distribution of YOY Colorado pikeminnow have been monitored in the Colorado River since 1982 (McAda and Ryel 1999). Density has been highly variable over that period, but YOY have been captured every year since monitoring began (Figure 3.7). Highest density of YOY Colorado pikeminnow occurred in 1985, 1986, and 1996 and lowest density occurred in 1984, 1995, and 1997. Figure 3.8 presents the distribution of YOY Colorado pikeminnow during the three years of highest density during the 1982–1997 sampling period (McAda and Ryel 1999). Young-of-the-year Colorado pikeminnow were found throughout the Colorado river downstream from the confluence with the Gunnison River, but were most abundant in the 65 mi between Moab and the mouth of the Green River. Although larval Colorado pikeminnow were collected upstream of the mouth of the Gunnison River in 1982 (McAda and Kaeding 1991b) and in 1995 (Anderson 1999), no YOY and only one yearling have ever been captured there (Osmundson and Burnham 1998). The number of YOY captured in the river between the mouth of the Gunnison River and Westwater Canyon has decreased since the mid 1980s, with no YOY Colorado pikeminnow captured upstream

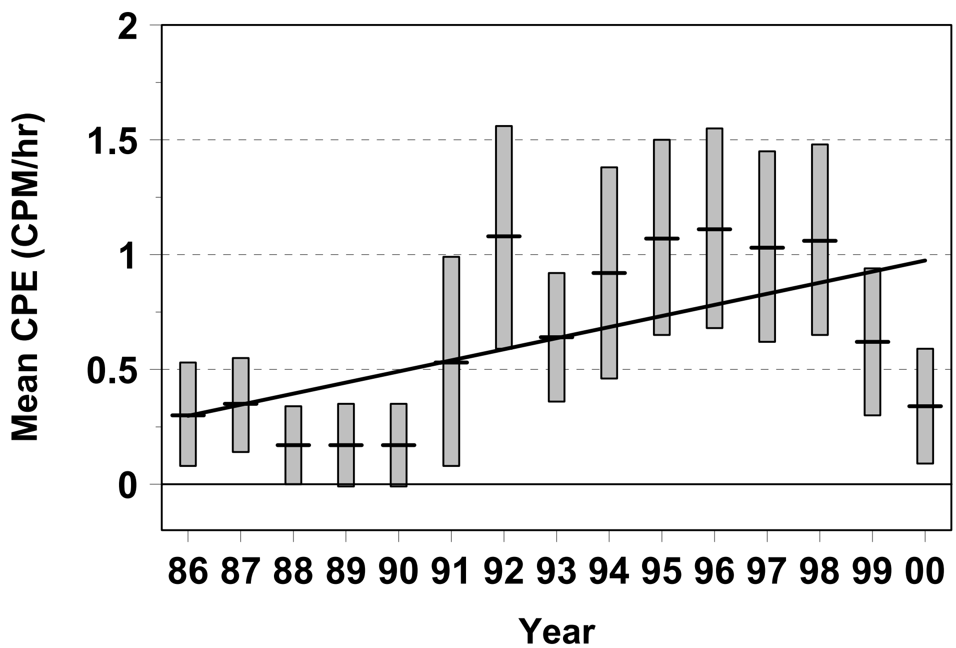

FIGURE 3.6. — Mean CPE (fish per hour) of Colorado pikeminnow captured with shoreline electrofishing during subadult and adult monitoring in the Colorado River. Data were excerpted from Figure 5 in McAda (2002a); bars indicate ± 1 SE.

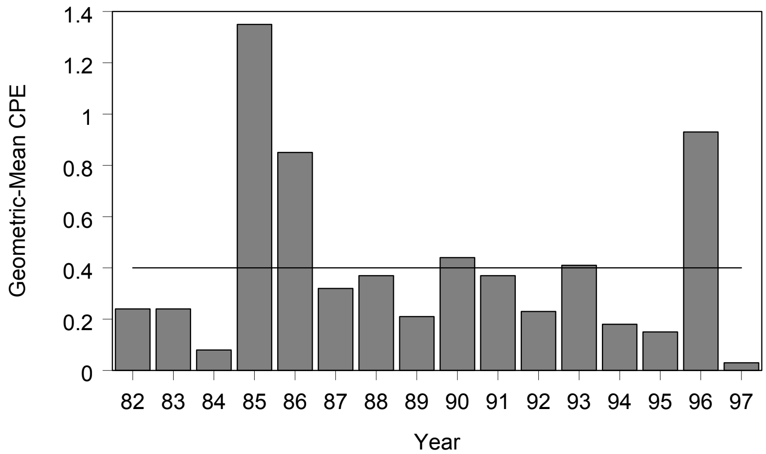

FIGURE 3.7. — Geometric-mean CPE (fish/10 m^2) for YOY Colorado pikeminnow collected from ISMP Reach 1 (RM 0–110) in the lower Colorado River, 1982–1997. Data were from McAda and Ryel (1999) and McAda et al. (1998). The horizontal line represents the mean value for the 16-yr period.

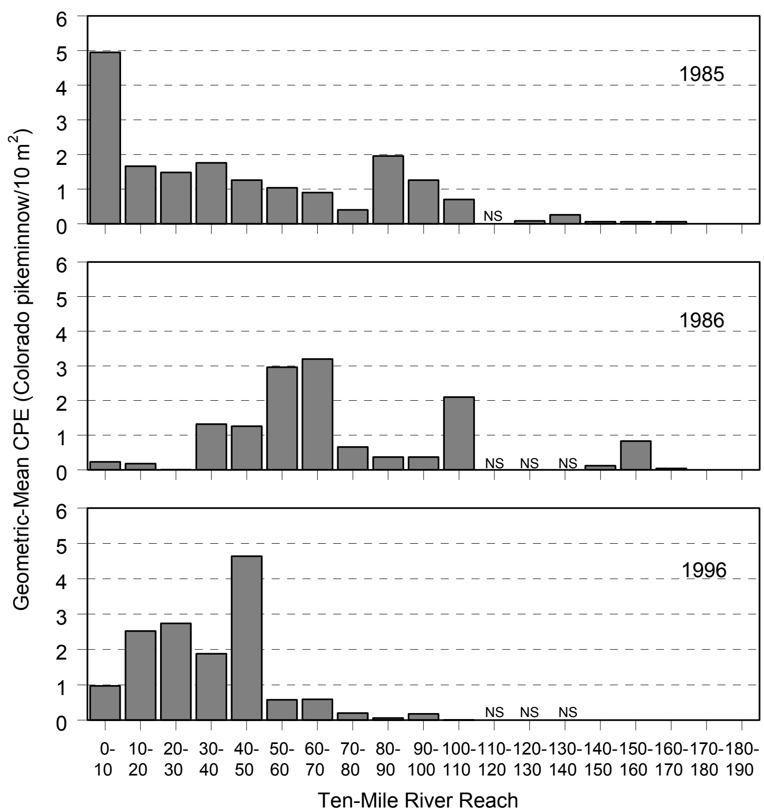

FIGURE 3.8. — Distribution of YOY Colorado pikeminnow in ISMP reaches 1 and 2 of the Colorado River during 3 yr of high autumn density. River mile 0 is the mouth of the Green River. Excerpted from Figures 6 and 7 in McAda and Ryel (1999). No samples were taken in reaches with NS.

from Westwater Canyon during autumn ISMP surveys since 1992 and only one captured each year from 1988 to 1992 (McAda and Ryel 1999). However, more intensive seining collections than done under ISMP captured one YOY Colorado pikeminnow in 1997 and one in 1998 in the Grand Valley downstream from the Gunnison River (K. Bestgen, personal communication).

Density of YOY Colorado pikeminnow was greatest in the lowest gradient reaches of the Colorado River, similar to distributional patterns in the Green River (Tyus and Haines 1991). This lower 60 mi of the river has a large number of backwaters and embayments (although not the largest, or the highest concentration of backwaters; Section 2.2.1) and the warmest water temperatures in the Colorado River upstream from Lake Powell (Osmundson 1999). Backwaters are warmer and more productive than the rest of the river (Wydoski and Wick 1998), and they provide important nursery habitat for small Colorado pikeminnow during the first year of their life (Tyus and Haines 1991).

Gunnison River. — Although semi isolated from the Colorado River population by construction of the Redlands Diversion Dam at RM 3.0 in 1917, a small, remnant population of Colorado pikeminnow persisted upstream of the dam (Figure 3.3). Burdick (1995) sampled the Gunnison River from the mouth of the North Fork of the Gunnison River downstream to its confluence with the Colorado River during 1992–1994. He captured five adult Colorado pikeminnow (mean total length, 637 mm; range, 497–847) in the Gunnison River between Hartland and Redlands dams. Four others were positively identified while electrofishing but were not captured. Two of the captured fish were ripe males found together in a large eddy at RM 33.7 on 14 July 1993. Of the remaining Colorado pikeminnow, one was captured at RM 33.5, one in the flooded mouth of Kannah Creek (RM 18.2) on May 5 1993, and another at RM 16.7 on the same day. Fish that were observed, but not captured were seen at RM 7.7, RM 30.8 and RM 32.9 in 1992 and at RM 48.4 in October of 1993. In earlier investigations, Valdez et al. (1982a) captured four adult Colorado pikeminnow between RM 26.7 and RM 33 and observed, but did not collect, four more between RM 22.1 and RM 31.4. The upstream limit of Colorado pikeminnow distribution in the Gunnison River is Hartland Diversion Dam, an impassible barrier at RM 59.9, about 57 mi upstream from Redlands Dam (Burdick 1995).

Burdick (1995) implanted seven adult Colorado pikeminnow with radio transmitters and followed their movements in the Gunnison River during 1993 and 1994. Two fish were captured upstream from Redlands Dam at RM 16.7 and RM 33.5. The other five were captured downstream from Redlands Dam and released upstream after radio tags were implanted. Four of those fish remained upstream from the dam for the life of their transmitters. The fifth fish remained in the river for 78 d before moving back downstream over the dam. It survived the 12-ft drop over the dam and was later recaptured in the pool immediately below it (B. Burdick, personal communication).

The radiotagged fish used most of the river between Redlands and Hartland diversions, but 48% of all radio contacts were made between RM 30 and RM 41.9 and 32% were made between RM 15 and RM 29 (Burdick 1995). All Colorado pikeminnow captures and observations except one were also in these two reaches. Radiotagged fish congregated in a short reach between RM 30 and RM 35 during the estimated spawning period in 1993, with four fish located between RM 32 and RM 33. Two ripe males were captured at RM 33.7 during this period, but no ripe females were collected. Occurrence of a congregation at the same location for 2 consecutive years during the estimated spawning period suggests that Colorado pikeminnow were spawning there. The reach contained numerous riffles with cobble and gravel substrates similar to reaches in other rivers identified as Colorado pikeminnow spawning areas (Lamarra et al. 1985; Harvey et al. 1993; Miller and Ptacek 2000).

Burdick (1995) used dip nets and seines to sample the larval and juvenile fish communities of the Gunnison River between Delta and Grand Junction, but failed to capture age-0 Colorado pikeminnow. However, Anderson (1999) captured one larval Colorado pikeminnow in a drift net located immediately downstream from Redlands Dam in 1992. The congregation of adults during the presumed spawning period in 1993 prompted Anderson (1999) to locate a drift-net sampling station at RM 29.3 from 1994 through 1996. He captured at least one larval Colorado pikeminnow at that site in each year. Based on radiotelemetry observations and the subsequent capture of larvae, it is likely the river between RM 30 and RM 35 contains one or more spawning sites that are repeatedly used by Colorado pikeminnow. Drift-net sampling at other stations in the Gunnison River also captured larval Colorado pikeminnow at RM 5.5 (above Redlands Dam) and at RM 0.7 (downstream from Redlands Dam) in 1995 and 1996 (Anderson 1999). These collections document Colorado pikeminnow spawning in the Gunnison River, but downstream collections do not help locate specific spawning sites because the larvae may have drifted downstream for an unknown distance.

Reconnecting fragmented river reaches is an important component of the Recovery Program (Wydoski and Hamill 1991), and the first fishway constructed under the Recovery Program was built on Redlands Dam (USBR and USFWS 1995). The fishway allowed fish to move between the two rivers for the first time in 80 yr. During seven seasons of operation, 50 different Colorado pikeminnow used the fishway. Seven of those fish used the fishway in two different years and one used it in three different years (totaling 59 occasions: 1 in 1996, 18 in 1997, 23 in 1998, 5 in 1999, 4 in 2000, 1 in 2001, and 7 in 2002 [Burdick 2001a, 2001b, 2002b]). No fish have used the fishway twice in the same year. The passage is operated continually from March through October, but all Colorado pikeminnow used the fishway in July, August, or September (Burdick 2001a, 2001b, 2002b). There is some movement back and forth between rivers as evidenced by use of the ladder by eight fish in two or more years. In addition, six other Colorado pikeminnow that have used the ladder have been recaptured in the Colorado River (Burdick 2001a). Because there is not a downstream trap on the ladder, it is not know when these fish moved back downstream over the diversion dam or how many other fish may have returned to the Colorado River and not been recaptured.

3.2.2 Habitat Use

Adults and Subadults. — Adult Colorado pikeminnow use a variety of habitats, but exhibit preferences for specific habitats during different periods of the year (Tyus and McAda

1984; Osmundson et al. 1995). In the Colorado River near Grand Junction, pools and slow runs (water velocity <2.0 ft/sec) accounted for 77–95% of all habitats used in winter (November through February; Osmundson et al. 1995). More than 74% of all observations during this period had mid-column velocities <1.0 ft/sec. Eddies and backwaters were the only other habitats used by Colorado pikeminnow in winter.

In spring (April–June), river discharge and water velocities increased and Colorado pikeminnow sought off-channel habitats with reduced water velocity and warmer water temperatures than the main river (Osmundson et al. 1995). In the Colorado River, backwaters and flooded gravel pits (combined) composed 45% of radiotagged Colorado pikeminnow locations in April, 49% in May, and 47% in June (Osmundson et al. 1995). Similar flooded habitats were also heavily used in the Yampa River during spring (Valdez and Wick 1983). These quiet, warm-water areas allow Colorado pikeminnow to minimize energy expenditures and begin somatic growth or gonad maturation sooner than would be possible if they were unable to escape the swift, cold water of the main channel (Valdez and Wick 1983). Other quiet habitats such as eddies and shorelines were used to a lesser degree (Osmundson et al. 1995).

Use of main-channel habitats increased as water levels receded to summer base flows (Osmundson et al. 1995). Gravel pits were no longer available and backwaters were fewer in number and smaller in size. Slow and fast runs accounted for 49–52% of habitats selected in summer (July–September; Osmundson et al. 1995), but eddies (9–16%) and pools (13–16%) were also used. Use of riffles was relatively low (3–10%) compared to other habitats, but was higher than observed in other seasons.

Osmundson et al. (1995) considered March and October to be transitional months. Habitat use was most similar to winter during these two transitional months, with heavy use of pools (March, 32%; October, 26%) and slow runs (43%; 61%). Backwaters (14%; 9%), eddies (4%; 7%) and fast runs (0%; 4%) were also used. Rapids and shorelines were not used, and flooded gravel pits were not available.

Comparing habitat use with habitat availability can determine which habitats are preferred by Colorado pikeminnow. Within the Grand Valley, Osmundson and Kaeding (1991) determined that radiotagged Colorado pikeminnow preferred river segments with complex channels (i.e., areas with islands, backwaters, and side channels) versus segments with simple channels (i.e., single channels with no side channels or islands). These braided areas provide a greater diversity of habitats for Colorado pikeminnow to exploit for resting or foraging and were preferred during all seasons of the year.

Osmundson et al. (1995) further distinguished habitat preferences by estimating relative occurrence of different meso-habitat types within the Colorado River in the Grand Valley. Eddies, backwaters, and pools (in order of preference) were preferred habitats during moderate summer flows in the Colorado River. Slow runs followed by fast runs were preferred during low summer flows. In winter, Colorado pikeminnow preferred pools, backwaters, and eddies (in order of preference).

Age-0 and Age-1. — Small Colorado pikeminnow are highly dependent on backwaters or shallow embayments for nursery habitat (Tyus and Haines 1991; Trammell and Chart 1999b, 1999c). Tyus and Haines (1991) sampled a variety of habitats in the two primary nursery areas of the Green River and found 84% of age-0 Colorado pikeminnow in backwaters, but they were also collected in shorelines, side channels, runs, and eddies. They reported that backwaters with age-0 Colorado pikeminnow were, on average, warmer and deeper than backwaters without small Colorado pikeminnow. Based on results subsequently reported by Tyus and Haines (1991), Archer et al. (1985) concentrated on sampling backwaters in the Colorado River, but also sampled other quiet-water habitats nearby. More than 98% of the small Colorado pikeminnow they collected were found in backwaters. Although backwaters are preferred habitat, young Colorado pikeminnow move between backwaters and the main channel in response to environmental variables, including changes in water temperature (McAda and Tyus 1984; Tyus 1991b).

More recently, Trammell and Chart (1999b) investigated habitat preferences of small Colorado pikeminnow in more detail. They divided backwaters into six categories, but two backwater types were found in greatest abundance in the lower Colorado River — scour channels and migrating sand waves. Scour channels are formed by the erosion of small channels behind large sandbars during spring runoff and are revealed by receding water levels. They are typically relatively deep and permanent. Migrating-sand-wave backwaters are formed by the movement of sand waves adjacent to sandbars and are relatively shallow and ephemeral. These habitats are also called embayments. Density of Colorado pikeminnow was highest in scour channels, and Colorado pikeminnow exhibited a significant preference for this backwater type in one of two study reaches in the Colorado River (Trammell and Chart 1999b). A similar study conducted in the lower Green River also revealed a strong preference for scour-channel backwaters (Trammell and Chart 1999c). On average, scour-channel backwaters were larger and deeper than other backwater types and often persisted in the same location for several years (Trammell and Chart 1999b). Persistence of these deep backwaters may play an especially important role in overwinter survival (Trammel and Chart 1999b). Winter habitat use of YOY Colorado pikeminnow has not been studied. Because they still occur in backwaters in late autumn (October–November) and are found there again in early spring (late March; McAda and Ryel 1999; Trammell and Chart 1999b, 1999c), it is presumed that backwaters remain important through winter. However, it is likely that young fish move in and out of backwaters in response to temperature changes (e.g., Tyus 1991b) and use of backwaters may decline as they grow.

3.2.3 Reproduction

Timing. — Colorado pikeminnow spawn as spring flows decrease and water temperatures increase (Haynes et al. 1984; Nesler et al. 1988; Tyus 1990, 1991a; McAda and Kaeding 1991b; Bestgen et al. 1998; Anderson 1999; Trammell and Chart 1999a). In the Green River basin, adults begin migrating to spawning areas as peak runoff is declining and water temperatures are increasing (Tyus 1990, 1991a). In the Colorado River, Colorado pikeminnow do not migrate to the extent that they do in the Green River, but migration occurs with movement beginning in response to the same environmental cues as observed in the

Green River basin (i.e., declining runoff and increasing water temperature; McAda and Kaeding 1991b). Based on back calculation of hatching date from total length of larvae (using equations developed by Haynes et al. 1984), McAda and Kaeding (1991b) estimated that spawning began in the Colorado River near Moab in late June 1985, early July 1982 and 1984, and late July 1983. It continued into early August in 1982 and 1985, and into early September in 1983 and 1984. Spawning began in the upper Colorado River in late June in 1985, mid July in 1982 and 1984, and mid August in 1983. Water temperatures were 18–22°C and river flow was 15–30% of the maximum discharge for the year when spawning began (McAda and Kaeding 1991b). In general, spawning occurred earlier during low-runoff years and later in higher-runoff years which has also been observed for the Green River basin (Tyus and Haines 1991; Bestgen et al. 1998).

Trammell and Chart (1999a) and Anderson (1999) collected drifting Colorado pikeminnow larvae from four sites in the Colorado River and three sites in the Gunnison River during 1992–1996. They estimated that spawning began as early as June 5 in 1994 and as late as July 11 in 1995 (Figure 3.9). The lowest runoff that occurred during the study was in 1994 and the highest was in 1995. Based on size of larvae and timing of captures, spawning in the lower Colorado River (near Moab) was estimated to begin earlier than in the upper river (near Loma, Colorado), with the greatest differences observed in 1994 and 1995, and the least difference observed in 1992. Spawning began 1 to 4 weeks after runoff peaked for the year at flows ranging from 8,000 to 37,000 cfs and shortly after river temperatures reached 17–18°C (Trammell and Chart 1999a; Anderson 1999). River temperatures were 20–22°C by the time spawning ended. These observations were similar to those reported for the Green and Yampa rivers during the same study period (Bestgen et al. 1998); however, spawning began at river temperatures as low as 16°C in the Yampa River (Bestgen et al. 1998). Bestgen et al.(1998) estimated spawning dates using otoliths, which is a more precise technique than the equations developed by Haynes et al. (1984). Errors of only a few days in estimated spawning date in the Colorado River could easily mean a 2–3°C difference in water temperature at initiation of spawning. Although some spawning may occur at cooler temperatures, most spawning in the Colorado, Green, and Yampa rivers occurs at water temperatures between 18 and 22°C (McAda and Kaeding 1991b; Tyus 1991a; Bestgen et al. 1998; Anderson 1999; Trammell and Chart 1999a).

Habitat. — Most Colorado pikeminnow spawning in the Green River basin occurs in one of two sites — lower Yampa Canyon on the Yampa River and Gray Canyon on the lower Green River (Tyus 1990, 1991a). These reaches are 26 and 45 mi long, respectively, but most spawning is believed to occur at one or two short segments within the two reaches. Spawning occurs over gravel-cobble substrates in riffles; adjacent pools are used for staging and resting (Tyus and McAda 1984).

Specific spawning sites in the upper Colorado River are not as well documented as those in the Green River basin, although successful spawning occurs every year (Anderson 1999; McAda and Ryel 1999; Trammell and Chart 1999a). McAda and Kaeding (1991b) reported a

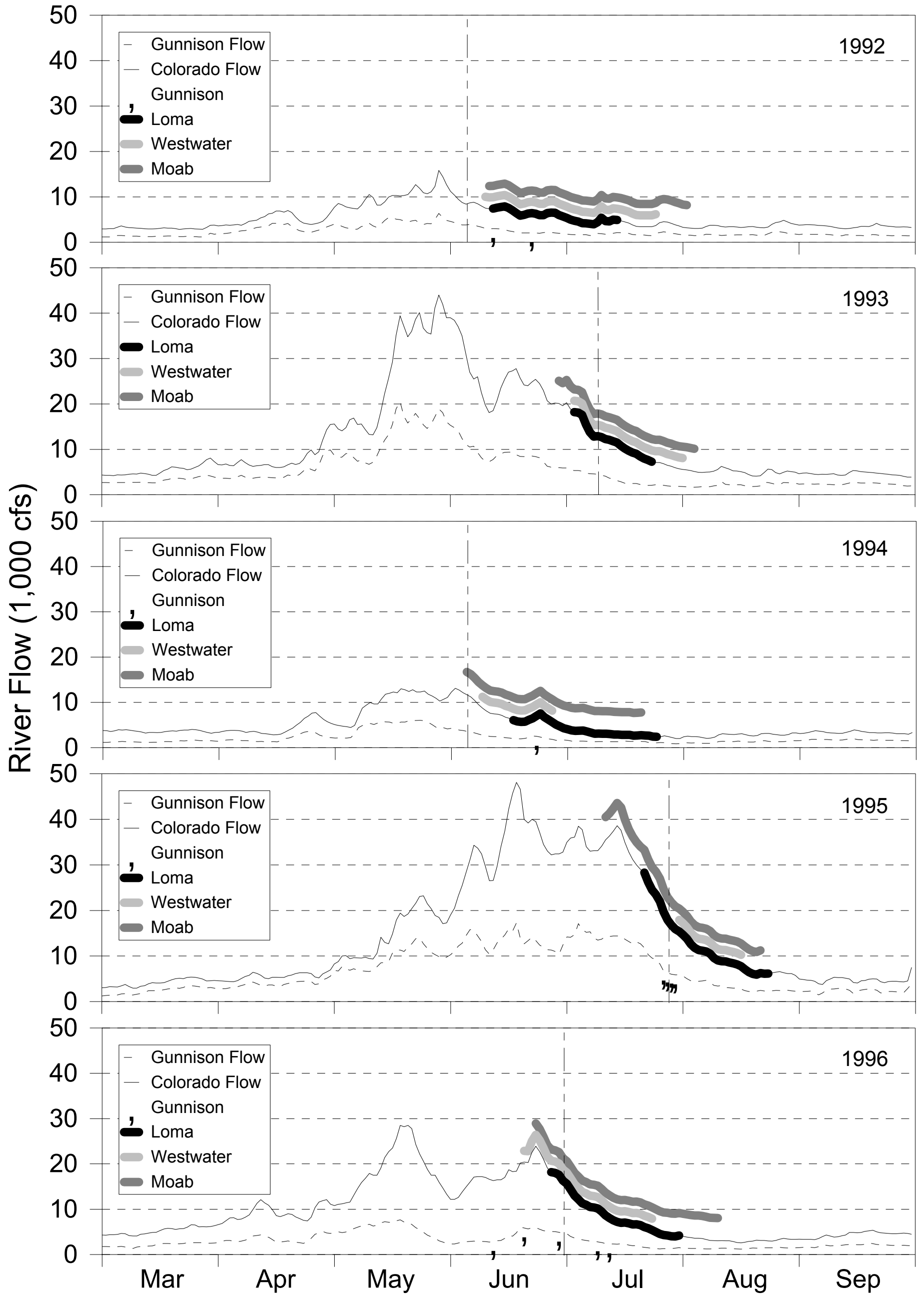

FIGURE 3.9. — Range of estimated spawning dates for Colorado pikeminnow in the Gunnison and Colorado rivers, 1992–1996. Spawning dates were calculated by Anderson (1999) and Trammell and Chart (1999a) for larval Colorado pikeminnow captured in drift nets, and are presented for all sampling sites combined in the Gunnison River and for three sampling sites (Loma, Westwater, and Moab) in the Colorado River. Depicted river flows were measured at USGS gages on the Gunnison River near Grand Junction and the Colorado River near the Utah-Colorado state line. Vertical line depicts the first day that maximum daily water temperature at the state-line gage reached 18°C.

presumed spawning aggregation of radiotagged Colorado pikeminnow upstream from the mouth of the Gunnison River in the first year of a 4-yr radiotelemetry study, but the aggregation was not repeated in subsequent years and most radiotagged fish remained scattered or in pairs during the presumed spawning period. They concluded that spawning is generally done by smaller groups and in more locations than occurs in the Green River basin. More recent data (Osmundson and Kaeding 1989a; Burdick 1997; D. Osmundson, unpublished data) support this hypothesis; i.e., many radiotagged adult Colorado pikeminnow remained separated throughout the presumed spawning period. However, recent efforts have located five more possible spawning sites based on aggregations of Colorado pikeminnow during the presumed spawning season: one in the Gunnison River near RM 32 (Burdick 1995) and one downstream from Redlands Diversion Dam (Burdick 1997, 2001a), two in the Colorado River between the confluence of the Gunnison River and Westwater Canyon, and one downstream from Westwater Canyon near Fish Ford (D. Osmundson, unpublished data). As observed by McAda and Kaeding (1991b), several of these aggregations could not be substantiated in subsequent years even though some efforts were made to collect or otherwise locate fish in the same area. However, sampling attempts were not made on a regular basis, but rather when opportunities presented themselves.

Aggregations of Colorado pikeminnow at one of the sites downstream from the mouth of the Gunnison River were documented in 3 different years. A total of 18 fish were collected from a pool-riffle complex in 1994 during the spawning period (D. Osmundson, unpublished data). Ten of these fish were ripe males and five others appeared to be females, but no eggs were emitted (sex of three others could not be determined). The area was sampled again during the presumed spawning period in 1998 and 12 fish were collected, including 7 ripe males and 4 apparent females (D. Osmundson, unpublished data). About 25 additional Colorado pikeminnow were observed during electrofishing, but could not be captured by the sampling crew (D. Osmundson, personal communication). Habitat changes that occurred during intervening years resulted in a 0.25-mi shift in the actual spawning site between the two years, but the specific attributes of the two sites were very similar. The area encompassed an island-cobble bar complex that was bisected by a chute channel. Most fish were found in eddy-pools along the island, but others were caught at the end of the chute channel where it emptied into the main channel. Colorado pikeminnow were probably spawning at the end of the chute channel where the cobble was very loose with large interstitial spaces, and using the nearby eddies along the island as resting areas between spawning events (D. Osmundson, personal communication). In 1999, nine more Colorado pikeminnow were captured at this site during the spawning season, including five ripe males and one ripe female (gentle pressure extruded eggs when the fish was captured [C. McAda, personal observation] and it was spawned in the hatchery later that day without hormone injections [M. Baker, personal communication]). Cobble-gravel bar complexes that are very similar to this site are found at many locations in the upper Colorado River (J. Pitlick, personal communication).

Although most adult Colorado pikeminnow occur in the upper Colorado River, larval data suggest that spawning also occurs in the lower river (Trammell and Chart 1999a). Differences in larval density between a sample site upstream from Westwater Canyon and one near Moab suggests that many larval Colorado pikeminnow captured at Moab were spawned downstream from Westwater Canyon (Trammell and Chart 1999a). Adult Colorado pikeminnow remain in that reach during the presumed spawning period (McAda and Kaeding 1991b), and one possible spawning site has been identified near Fish Ford (D. Osmundson, personal communication).

In contrast with the Green River basin where known spawning sites are in restricted, canyon-bound reaches that are relatively stable (Tyus 1991a), spawning sites in the upper Colorado River are in meandering, alluvial reaches susceptible to considerable change during high flows. Lack of repetitive use of specific sites may be related to changes that occur during the scouring flows of spring runoff. Colorado pikeminnow have been precluded from upstream canyon reaches of the upper Colorado River since the early part of this century when low-head diversion dams were constructed on the Gunnison and Colorado rivers near Grand Junction (Burdick and Kaeding 1990). These dams precluded movement into what had been occupied habitat. It is not known whether Colorado pikeminnow have been excluded from historic spawning habitats and they are currently using areas that they would have bypassed in the past, or if some spawning has always occurred in the Grand Valley. However, Colorado pikeminnow also spawn in an alluvial reach of the San Juan River (Ryden and Ahlm 1996) with habitat attributes very similar to sites within the Grand Valley (Bliesner and Lamarra 2000; Miller and Ptacek 2000). As with the Colorado River, it is not known whether Colorado pikeminnow spawned farther upstream before their movement was blocked by instream diversion dams.

The Colorado pikeminnow is a broadcast spawner that deposits eggs on cobble substrates in riffles and runs (Tyus 1991a). Lamarra et al. (1985) described a known spawning site on the Yampa River as being comprised of cobble substrate with large interstitial spaces. Embryos have not been collected at the spawning bars, but it is hypothesized that they settle into the interstitial spaces of the cobble substrate for incubation. Hamman (1981) documented that Colorado pikeminnow embryos adhered to clean cobble substrate in hatchery raceways, so it is likely that a similar process occurs in the river. A congener, northern pikeminnow *P. oregonensis*, spawns over similar substrate in the St. Joe River, Idaho, where eggs were found up to 15 cm below the substrate surface (Beamesderfer and Congleton 1982).

After deposition and fertilization, the embryos incubate in the cobble for 4–7 d depending on water temperature (Hamman 1981; Marsh 1985; Bestgen and Williams 1994). The larvae remain in the gravel for another 6–7 d after hatching before emerging from the substrate and becoming entrained in the river current (Bestgen et al. 1998). Colorado pikeminnow larvae may drift downstream for many miles before settling in low-gradient reaches with abundant backwaters and other quiet-water habitats (Tyus and Haines 1991; Bestgen et al. 1998; Anderson 1999; Trammell and Chart 1999a). As discussed above, the primary nursery area in the Colorado River is the 60-mi section upstream from the mouth of the Green River (McAda et al. 1994b; Trammell and Chart 1999b).

Influence of River Flow on Reproductive Success. — Production of Colorado pikeminnow larvae was monitored with drift nets at five sites in the Colorado River from 1992 to 1996 (Anderson 1999; Trammell and Chart 1999a). Density of drifting larvae varied among sites, but larvae were consistently most abundant at two sampling sites — near Loma (Anderson 1999) and near Moab (Trammell and Chart 1999a) — with highest drift density at both sites occurring in the high water year of 1995. Density was also high in 1996 at Moab, but not at Loma. Relative density of drifting larvae at both sites was lowest during the low-water years of 1992 and 1994. Overall, density of drifting larvae was highest in years with moderate to high spring flows and lowest in years with low spring flow (Anderson 1999; Trammell and Chart 1999a).

McAda and Ryel (1999) used principal components analysis to synthesize the relationship between seasonal river flows and relative density of YOY Colorado pikeminnow in autumn. Their results indicated that antecedent flows were just as important in predicting the density of YOY Colorado pikeminnow in autumn as were flows that occurred in the year of reproduction. The three years with highest YOY density (1985, 1986, and 1996) clustered together and were related to high peak flows (> 50,000 cfs) in the previous year and moderately high flows (30,000–40,000 cfs) in the year when the young fish were produced (Figure 3.10). In general, variables describing spring flow and the previous year's spring flow had positive effects on density of YOY Colorado pikeminnow, but number of days that flow exceeded 50,000 cfs in the year of production and relatively high flows during August negatively affected autumn density. Tyus and Haines (1991) also noted that high flows in the Green River during the summer larval-drift period resulted in low density of YOY Colorado pikeminnow in autumn.

Trammell and Chart (1999a) compared density of drifting larvae in summer and density of YOY Colorado pikeminnow in autumn, and concluded that there was not a significant linear relationship between the two. However, the lack of a relationship was due to 1995, when drift density was high and autumn density in backwaters was low (Figure 3.11). Exclusion of the 1995 data point as an outlier produces a significant relationship between density of larvae and autumn density of early juveniles. This loss of larvae is most likely related to extended runoff during 1995. May and June 1995 were exceptionally wet (Section 2.1.4), and flows remained high through most of the spawning and drifting period. Spawning was delayed, and YOY Colorado pikeminnow were the smallest observed during 15 yr of monitoring (McAda and Ryel 1999). Although it is impossible to determine the fate of the larvae produced in 1995, they were most likely carried downstream of the nursery area and into Lake Powell, Utah. Under predevelopment conditions, the young fish would have probably been carried further downstream to suitable nursery habitats in Glen Canyon, Utah or further downstream. But under current conditions, they were probably lost to the large number of introduced predators in Lake Powell (Valdez 1990). Although the high flows of 1995 resulted in poor survival of Colorado pikeminnow larvae through autumn, they were important in setting conditions for the very successful reproduction observed in 1996. This was a repeat of conditions in 1983–1985, when high flows in 1983 and 1984 produced poor survival of young Colorado pikeminnow, but may have contributed to higher than average density in 1985 (McAda and Ryel 1999).

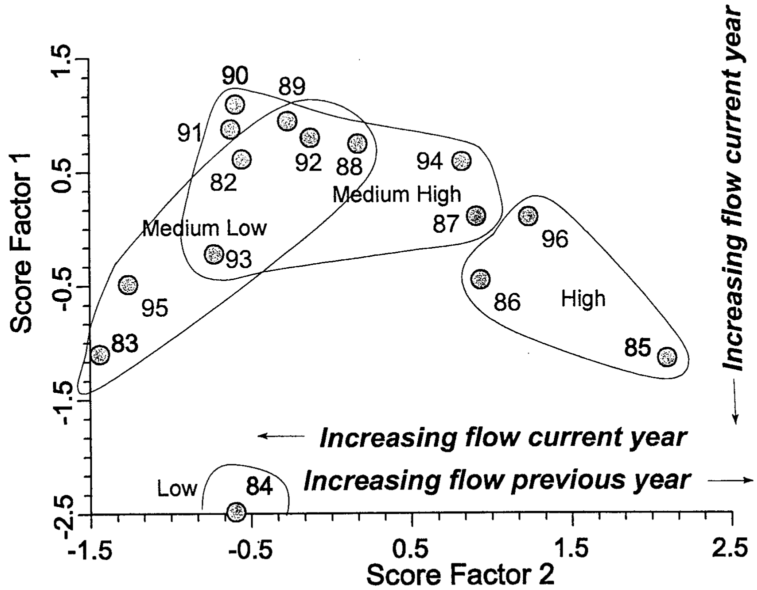

FIGURE 3.10. — Plot of scores for factors 1 and 2 determined by principal components analysis of 13 river flow variables compared with relative density of YOY Colorado pikeminnow. The year of each case is indicated. The four groups of enclosed scores refer to four levels of YOY Colorado pikeminnow density in autumn, with highest relative density grouped on the right side of the graph. Figure 8 in McAda and Ryel (1999). Factor loadings of flow variables are in Table A.29.

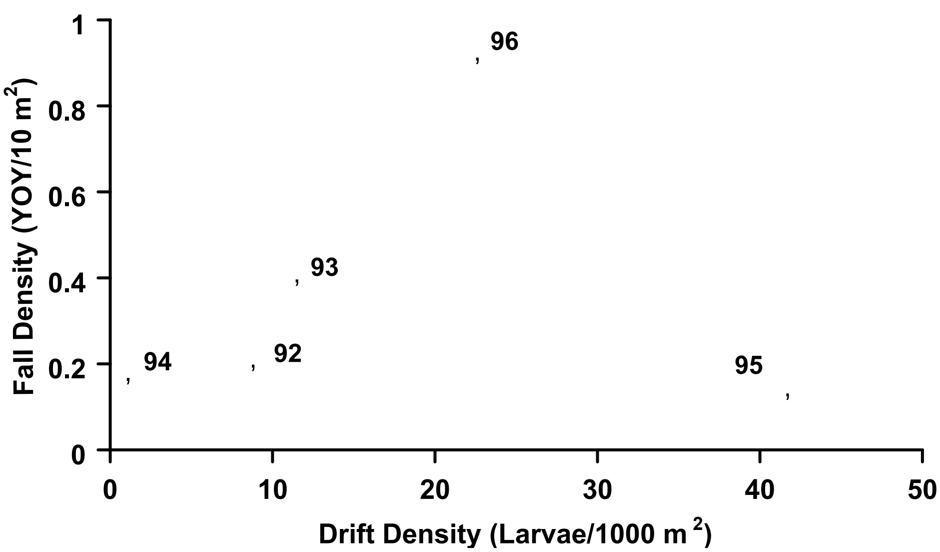

FIGURE 3.11. — Relationship of summer density of drifting larvae at Moab to autumn density of YOY Colorado pikeminnow in the lower Colorado River as determined by autumn ISMP seine samples. Larval density from Table 8 in Trammell and Chart (1999a); autumn density from Table 13 in McAda and Ryel (1999).

Harvey et al. (1993) studied a Colorado pikeminnow spawning bar at RM 16.5 in the Yampa River and concluded that bar formation occurred at flows between 400 and 5,000 cfs. Receding water levels at low to moderate flows cleaned silt and sand from the cobble substrate. Because spawning sites are scattered in the Colorado River, it is difficult to develop a model describing specific spawning habitat as was done by Harvey et al. (1993) for the Yampa River bar. However, Pitlick and Van Steeter (1998) showed that 80% of the sediment load in the Colorado River is carried by about 20% of the flows (Section 2.2.2). After the high runoff years of 1983–1986, a 7-yr period of below average runoff allowed sediments to build up in the Colorado River within the Grand Valley. The sediment accumulation filled the interstitial spaces of the cobble bars and probably reduced spawning success. The high flows of 1993 and 1995 moved substantial amounts of sediments out of the Grand Valley (Pitlick and Van Steeter 1998) which cleaned the interstitial spaces in the cobble bars and provided "high quality" spawning habitat for Colorado pikeminnow.

Although high spring flows are necessary to move sediment and clean cobble, high flows appear to be detrimental to reproductive success (herein defined as number of larvae produced and their subsequent survival until autumn) in the year that they occur. Low density of YOY Colorado pikeminnow occurred in high as well as low flow years. High peak flows are generally followed by extended high summer flows which delay Colorado pikeminnow spawning (McAda and Kaeding 1991b; Bestgen et al. 1998). The extended high flows may also reduce the number and size of backwaters in nursery areas (Section 2.2.1), decreasing the probability that small fish will be deposited in quiet habitat rather than be carried further downstream (Tyus and Haines 1991). In the Colorado River, they may be carried into Lake Powell, where large numbers of introduced predators occur (Valdez 1990). However, the clean cobble persists to enhance hatching success in the following year. A moderate flow would then be adequate to remove sediments deposited between runoff events. The clean cobble would assist hatching success and moderate flows would allow for earlier spawning, a longer growing season and more backwater habitats for the small fish to settle in.

Biological factors may also be involved. Density of three nonnative predators and competitors is reduced in years with moderate to high spring runoff (>30,000 cfs; Section 3.1.3). Although they remain common, a temporary reduction in their abundance in years with moderate to high runoff would reduce their negative effect on age-0 Colorado pikeminnow and allow more young fish to survive to autumn.

Number of adult Colorado pikeminnow may also be a factor, although density of YOY Colorado pikeminnow in autumn has fluctuated dramatically despite a constant increase in the adult population over the last 10 yr (Section 3.2.1). More adults should result in more fertilized eggs, but the continued variability in autumn density indicates that suitable environmental conditions are required to produce large numbers of young fish.

3.2.4 Growth

Age-0 and Age-1. — Larval Colorado pikeminnow are 6–9 mm long at swim-up (Hamman 1981) and have an average length of about 35 mm (1982–1996) at the end of their first growing season in the Colorado River (McAda and Ryel 1999). Average length of Colorado pikeminnow at the end of their first growing season was variable among years and ranged from 20.5 mm in 1995 to 63.3 mm in 1994, but usually fell between 30 and 40 mm (McAda and Ryel 1999; Trammell and Chart 1999b). Average length of Colorado pikeminnow at the end of their first growing season was significantly correlated with accumulated temperatures units for spring, summer, and autumn (McAda and Ryel 1999; Trammell and Chart 1999b). However, a similar relationship was not found for the Green River (Converse et al. 1999). Timing of Colorado pikeminnow spawning varies with timing, magnitude, and duration of peak runoff; therefore spawning occurs earlier in low runoff years and later in high runoff years. The extreme variation in fish length in 1994 and 1995 resulted from low runoff with an abrupt transition to base flow in 1994, and high and extended runoff in 1995 — Colorado pikeminnow spawned early in 1994 and late in 1995.

Young Colorado pikeminnow continued to grow between autumn and spring in most winters, but most growth probably occurred in late autumn before onset of winter and low water temperatures (McAda and Ryel 1999). Colorado pikeminnow were significantly longer in spring than they were the previous autumn in 7 of 9 winters monitored by McAda and Ryel (1999), increasing from an overall mean length of 39.3 mm in autumn to 49.7 in spring. Overwinter mortality varied among years (mean, 49.8; range, 0–93%) and showed a trend toward improved overwinter survival with increasing fish size in autumn, but the relationship was not significant (Figure 3.12). However, Trammell and Chart (1999b) showed a significant relationship between fish size in autumn and overwinter survival during their 5-yr study in two 10-mi reaches of the lower Colorado River. Size-dependent mortality (i.e., small fish died ,or were displaced, at a higher rate than larger fish) was documented in only 1 of the 9 winters between 1988 and 1997 (McAda and Ryel 1999) — the year of smallest mean size in autumn. However, it does not appear to play as important a role in first year survival of Colorado pikeminnow as has been previously hypothesized (Kaeding and Osmundson 1988). The most important predictor of relative density of age-1 Colorado pikeminnow in spring was relative density of age-0 Colorado pikeminnow the previous autumn (Figure 3.13), although the relationship was heavily influenced by high catch rates in autumn 1996 and spring 1997 (McAda and Ryel 1999).

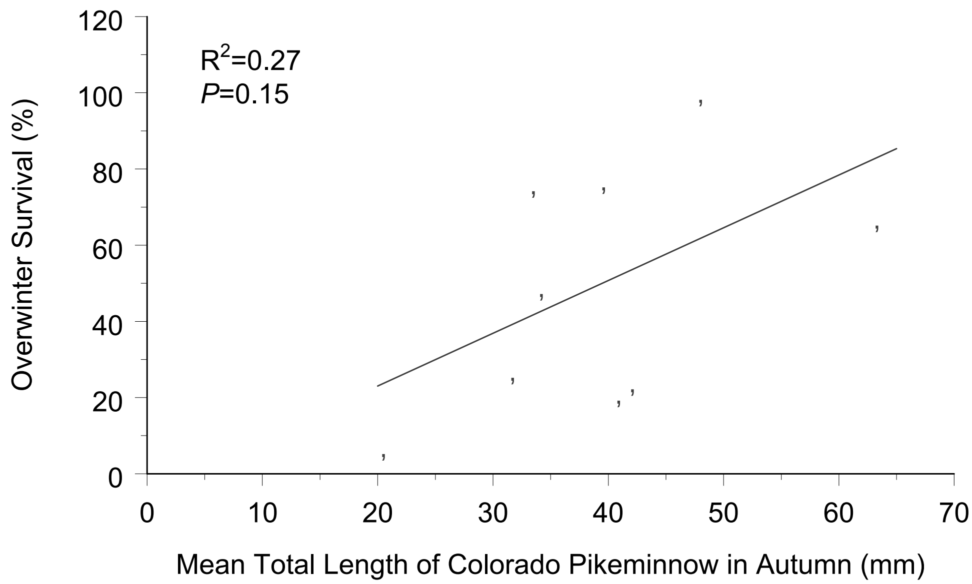

FIGURE 3.12. — Relationship between mean total length (mm) of YOY Colorado pikeminnow in autumn and overwinter survival in the lower Colorado River, autumn 1988–spring 1997. Figure 11 in McAda and Ryel (1999).

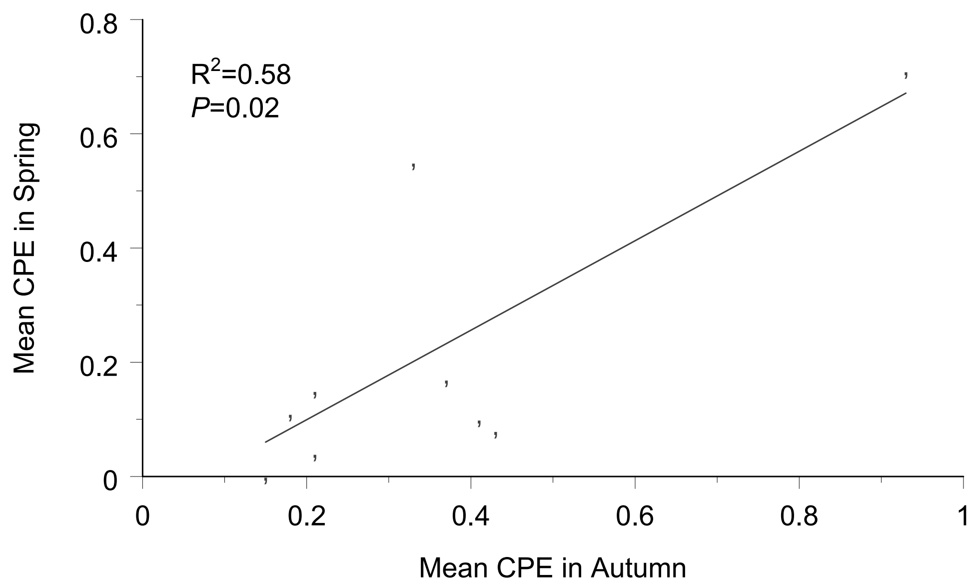

FIGURE 3.13. — Relationship between mean CPE of YOY Colorado pikeminnow in autumn and mean CPE of age-1 Colorado pikeminnow the following spring in the lower Colorado River, 1988–1997. Figure 10 in McAda and Ryel (1999).

Adults and Subadults. — As with most fish, growth of Colorado pikeminnow is rapid at first and then declines as they age. Based on scale annuli, growth of juvenile Colorado pikeminnow in the Colorado River averaged 60–80 mm/yr between ages 0 and 4, and declined to about 32 mm/yr by age 6 when they were 375–472 mm long (Osmundson et al. 1997a). These values were comparable to fish of similar ages from the Yampa and Green rivers (Seethaler 1978; Hawkins 1992). Fish older than age 6 could not be reliably aged with scales, but simulations indicated that fish averaged 550 mm TL at age 10, 600 mm at age 15, 700 mm at age 25, and 800 mm at age 32 (Osmundson et al. 1997a). However, the simulations also indicated considerable variation in ages for fish of similar size. Based on recaptured fish, annual growth averaged 43 mm for fish 400–449 mm long and declined to 5 mm for fish 850–899 mm long.

Effect of Water Temperature on Growth. — Water temperature during the growing season was significantly related to size of YOY Colorado pikeminnow in autumn (McAda and Ryel 1999; Trammell and Chart 1999b). Laboratory studies determined that growth of YOY Colorado pikeminnow is maximized at 25°C, and that growth at 15, 20, and 30°C was 18, 54, and 51% of maximum (Black and Bulkley 1985a). Using these data and data from growth of yearling Colorado pikeminnow in ponds (Osmundson 1987), Kaeding and Osmundson (1988) estimated that growth ceased at water temperatures less than 13°C. Other laboratory studies indicated that 25°C was the preferred temperature for yearling and subadult Colorado pikeminnow (Black and Bulkley 1985b). Preferred temperature is generally considered optimum for many physiological processes including growth (e.g., Magnuson et al. 1979). Therefore, water temperatures of 25°C would be optimum for growth of all age classes of Colorado pikeminnow.

Extended spring flows delay warming of the river, which in turn reduces growth of YOY Colorado pikeminnow. Kaeding and Osmundson (1989) suggested that early summer flows in the Colorado River be sharply reduced through modified reservoir operations, which would provide temperatures suitable for spawning earlier than might otherwise occur and, therefore, provide a longer growing season for YOY Colorado pikeminnow. Warmer water temperatures would benefit growth of older fish as well. However, Osmundson et al. (1995) later modified that recommendation because the abrupt reduction in flows eliminated the transition period from spring highs to summer base flows. This transition period plays an important role in the riverine ecosystem. Abrupt changes in flows can have detrimental effects such as stranding young fish or benthic invertebrates, and disruption of riverine food webs that in turn negatively affect the native fish community (Stanford 1994).

Increasing spring peaks to more closely mimic historic flows could provide higher summer water temperatures while still maintaining the transition period between spring highs and base flows. Releasing more water during peak runoff means that less water needs to be released in early summer and base flows are reached sooner. Reaching base flow as early as possible in the growing season increases water temperature and results in enhanced growth for all size classes of Colorado pikeminnow.

Water temperature can also affect distribution of fishes. Average water temperatures in the Gunnison River near Delta are about 2°C less than temperatures near the mouth (Section 2.2.5). Although a 2°C difference in water temperature may seem small, the cumulative effects of such a difference can be biologically important. Osmundson (1999) determined temperature suitability of two sites on the Gunnison River for growth of Colorado pikeminnow and developed an index (measured in accumulated temperature units [ATUs]) to compare water temperatures among sites. He used a technique described by Kaeding and Osmundson (1988) in which mean daily temperatures are converted to values relative to maximum growth potential (1.0) at optimum water temperature (25°C). Data from the Yampa River suggests that upstream reaches with about 40 ATUs mark the upper limit of year-round home ranges of Colorado pikeminnow, although some seasonal use occurs in cooler, more upstream reaches (Osmundson 1999). One radiotagged fish moved upstream to the Hartland Diversion (RM 60) at Delta, but it did not remain there and most Colorado pikeminnow use was between RM 15 and 41 of the Gunnison River (Section 3.2.1; Burdick 1995). Osmundson (1999) calculated an average of about 40 ATUs for the Gunnison River at RM 35, but the average dropped to 32 ATUs upstream near Delta (RM 57). He estimated that the thermal regime of the Gunnison River near Delta could be increased from an annual average of 32–46 ATUs by increasing average June, September, and October temperatures by 1°C and average July and August temperatures by 2°C. This temperature increase would expand optimum habitat in the Gunnison River by about 25 mi and thereby provide maximum benefits from the Redlands fishway.

Based on his analysis, Osmundson (1999) recommended exploring the feasibility of modifying upstream releases (e.g., construction of selective withdrawals on one or more Aspinall Unit dams) to increase water temperatures in the Gunnison River near Delta. Because the potential to increase water temperature by modifying Aspinall Unit operations is uncertain, the Recovery Program funded a preliminary study to evaluate the feasibility and potential effects of changing water temperature in the Gunnison River (2001 SOW 107 — Gunnison River temperature modeling and potential impacts of modifications to Aspinall reservoir operations).

3.2.5 Summary of Seasonal Flow-Habitat Relationships for Colorado Pikeminnow

Spring. — Spring flows create and maintain habitats utilized throughout the year by all age classes of Colorado pikeminnow. Spring flows inundate floodplains and tributary mouths to provide warm, off-channel habitats for growth and conditioning of fish (Table 3.6). This habitat is especially important for gonad maturation and conditioning of adults in preparation for the upcoming spawning season. Increasing flows associated with spring runoff also provide important cues to prepare fish for migration to spawning areas.

Spring flows create and maintain habitats used by Colorado pikeminnow year round. Moderate to high spring flows mobilize the river bed and flush fine sediments from spawning gravels in preparation for spawning. High spring flows are also channel-forming flows that maintain channel complexity, scour side channels, and build backwaters. In-channel features

Table 3.6. — Qualitative relationships between river flow and Colorado pikeminnow habitat.

Season	Life Stage	River[a]	Habitat Maintenance Objective
Spring	Adults/ subadults	CO, GU	• Increasing flows associated with the beginning of spring runoff to cue fish to prepare for the upcoming migration and spawning period.
		CO, GU	• Flows sufficient to inundate floodplain habitats to provide warm, food-rich environments for growth and gonadal maturation in preparation for spawning.
		CO, GU	• Flows sufficient to scour vegetation from river banks and side channels to maintain habitat complexity and provide the suite of habitats used by adults in other seasons.
		CO, GU	• Flows that are sufficient to scour sediment from cobble/gravel bars in potential spawning areas increase survival of eggs and larvae.
		CO, GU	• Flows sufficient to mobilize the bed on a widespread basis in both runs and riffles; fines are flushed from the substrate and interstitial spaces are increased to maintain benthic productivity for foodweb linkages.
	YOY/ Juveniles	CO	• Flows sufficient to transport sediment and build in-channel sand bars for backwater habitat in summer, autumn, and winter.
		CO	• Flows sufficient to reduce abundance of nonnative fishes (competitors and predators) in backwater habitats used in summer, autumn, and winter.
Late Spring/ Early Summer	Adults	CO, GU	• Declining flows and increasing water temperatures that provide cues to initiate migration and spawning.
		CO, GU	• Flows sufficient to provide a migration corridor for migrating adults.
		CO, GU	• Flows sufficient to prevent sedimentation on cobble/gravel bars that could smother eggs or embryos.
Summer/ Autumn	Adults	CO, GU	• Stable base flows that maximize preferred habitats and provide sufficient water depth for fish to move among habitats used for foraging and resting.
	YOY	CO, GU	• Declining flows that provide sufficient volume to transport drifting larvae, but not so high that larvae are transported through the nursery area before they are deposited into low velocity habitats.
		CO	• Stable base flows that maximize the amount of backwater habitats available to YOY and small juveniles.

TABLE 3.6. — Continued.

Season	Life Stage	River	Habitat Maintenance Objective
Winter	Adults/ subadults	CO	● Stable base flows that maximize preferred habitats and provide sufficient depth for fish to move among habitats used for foraging and resting.
	YOY/ Juveniles	CO	●Stable base flows that maximize the amount of backwaters available to YOY and small juveniles.

[a] CO = Colorado River; GU = Gunnison River.

created during these high flows provide habitats for all life stages in the remaining seasons of the year (Section 3.2.2). An extended period without channel-forming flows allows extensive silt and sand deposits that can become stabilized with emergent vegetation. Higher flows are then required to recreate and maintain these habitats (Section 2.2.2).

High spring flows may also temporarily reduce abundance of nonnative fishes that can compete with or prey on young Colorado pikeminnow. This temporary reduction may increase the survival of small Colorado pikeminnow during this narrow window of opportunity.

Summer–Autumn. — Decreasing flows and increasing water temperatures trigger spawning. Extended high flows during this period delay spawning and decrease the length of the growing season available to YOY fish. Extended high flows also decrease the size and surface area of backwaters, and may carry drifting larvae downstream of the nursery area and into Lake Powell before they settle out.

Stable base flows maximize the amount of backwaters available to young Colorado pikeminnow. Based on limited data, size and surface area of backwaters are maximized in the Colorado River at flows of 3,000–4,000 cfs. However, backwaters were available at all flows observed. Stable flows allow water temperatures to warm, which increases growth of young fish. Deep, stable backwaters provide the “best” habitat for YOY Colorado pikeminnow; however, annual changes in configuration of sand bars in nursery areas prevent identification of a specific flow, or range of flows, that maximizes backwater habitats.

Subadult and adult Colorado pikeminnow use a variety of habitats during summer and autumn. Flows should be low enough to maximize the availability of a wide variety of habitats, but should allow for efficient movement among these habitats.

***Winter*. —** Young-of-the-year Colorado pikeminnow continue to use backwaters throughout the winter, although use of other habitats increases as the fish grow. Flows that maximize backwater area continue to be important for YOY Colorado pikeminnow through winter.

Subadult and adult Colorado pikeminnow prefer pools and slow runs during winter. These deep, relatively low-velocity habitats allow fish to minimize movement and conserve energy during the critical cold-water period. Flows that maximize pool and slow run habitats are important for subadult and adult Colorado pikeminnow.

3.3 RAZORBACK SUCKER

The razorback sucker is a large catostomid endemic to the Colorado River basin of the western United States (Minckley 1973). The species belongs to a monotypic genus that is distinguished by a prominent dorsal keel that rises immediately posterior to the occiput (Minckley 1973). Large individuals may reach a meter in length and weights of 5–6 kg (Minckley 1973), but most adults captured in the upper basin are less than 650 mm long and weigh less than 3 kg (McAda and Wydoski 1980; Tyus 1987; Tyus and Karp 1990). It is long-lived, and individuals may exceed 40 yr of age (McCarthy and Minckley 1987). The historic distribution of razorback sucker has been reduced by 75% (Minckley et al. 1991) and its extremely low abundance within remaining habitat caused it to be listed as endangered under the ESA (USFWS 1991).

3.3.1 Distribution and Abundance

General. **—** The razorback sucker was once widely distributed in the warm-water rivers of the Colorado River basin, but its distribution and abundance had been substantially reduced by the latter part of the 20th Century (Minckley et al. 1991). The largest population remaining in the basin occurs in Lake Mohave on the lower Colorado River, where an estimated 23,300 individuals currently survive (Marsh 1994). A much smaller population is found in Lake Mead (ca 460 individuals; Holden et al. 1999).

The only remaining riverine populations occur in the upper Colorado River basin, with the largest occurring in the middle Green River (Minckley et al. 1991). Lanigan and Tyus (1989) estimated the population size as 924 individuals (95% CI, 758–1,138) using mark-recapture data from 1980 to 1988. Modde et al. (1996) reestimated population size using mark-recapture data from 1980 to 1992 and a different (open vs closed [used by Lanigan and Tyus 1989]) model. They estimated population size at 524 individuals (95% CI, 351–696). These two estimates do not necessarily indicate a decline in the population, but may reflect the different models used to make the estimates. Modde et al. (1996) were also able to document limited recruitment to the middle Green River population based on occurrence of small adults. A much smaller population occurs in the lower Green River near the mouth of the San Rafael River (Chart et al. 1999).

Colorado River. **—** In the Colorado River upstream from Lake Powell, most razorback suckers have been captured in the Grand Valley (Loma to Palisade) near the confluence of the Gunnison and Colorado rivers (Figure 3.14). However, their abundance has decreased to the point that they are only infrequently captured there. During intensive efforts specifically targeted at known concentration areas, Kidd (1977) and McAda and Wydoski (1980) captured a combined total of 54 razorback suckers in 1974 and 204 in 1975 from two gravel-pit ponds connected to the Colorado River near Grand Junction. These numbers reflect the combined total of independent collections, but probably include some recaptures of the same fish because sampling was done in the same areas and Kidd (1977) did not mark fish before release. All of these fish were adults that exhibited signs of old age such as large size,

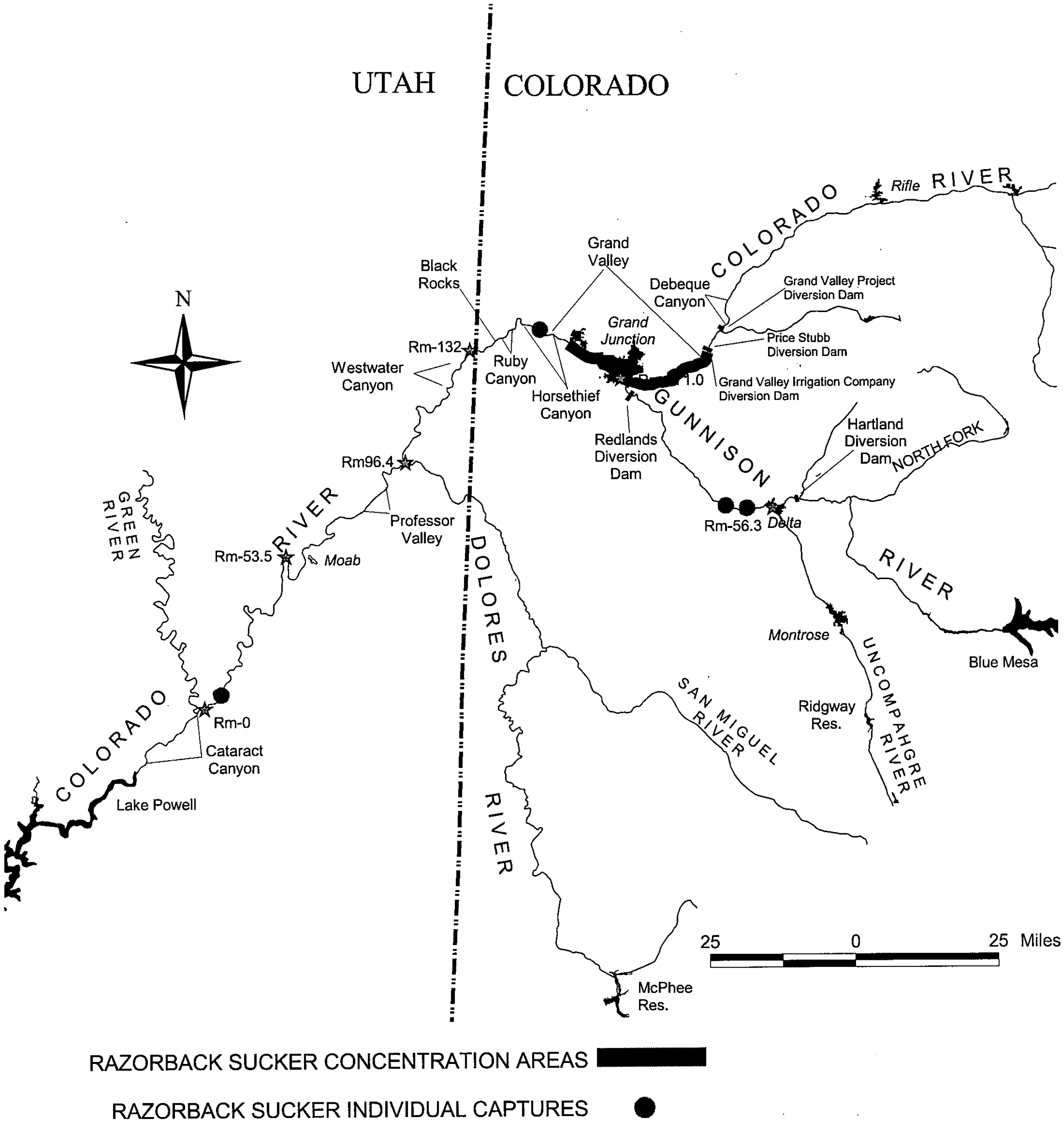

FIGURE 3.14. Distribution of razorback sucker in the upper Colorado and Gunnison rivers.

missing eyes, and heavy scarring (C. McAda, personal observation). A variety of investigators have sampled the Colorado River in subsequent years, but sampling effort varied considerably and sampling did not always target razorback sucker. The high numbers of razorback suckers captured in 1975 were not repeated in subsequent years (summarized by Osmundson and Kaeding 1991). The highest number captured in later years was 30 fish that were collected in 1982 from the same gravel-pit ponds sampled by Kidd (1977) and McAda and Wydoski (1980). Total fish captured declined dramatically after 1975, and few wild razorback suckers have been captured in recent years (Figure 3.15). Only 11 wild razorback suckers have been collected in the Grand Valley since 1990 despite intensive sampling in some years (Osmundson and Kaeding 1991; CDOW and USFWS, unpublished data). All of these fish were removed from the river to support propagation activities for the Recovery Program (M. Baker, unpublished data).

Although most razorbacks suckers have been collected in the Grand Valley, they have also been collected both up and downstream of the area. Kidd (1977) reported 22 razorback suckers from the Colorado River near DeBeque, Colorado (RM 209.7) in 1974–1975. No razorbacks have been collected from that reach since then (Valdez et al. 1982b; Burdick 1992). Burdick (1992) captured one razorback sucker from a gravel pit pond along the river at RM 234.8 and discovered a small population in another gravel-pit pond at RM 204.5. About 75 razorback suckers were captured from the second pond, but DNA analysis revealed that they were siblings. They were probably offspring from two or three razorback suckers trapped in the pond during the high-water years of 1983 or 1984. Three razorback suckers from this pond were incorporated into the propagation program, but their close relationship

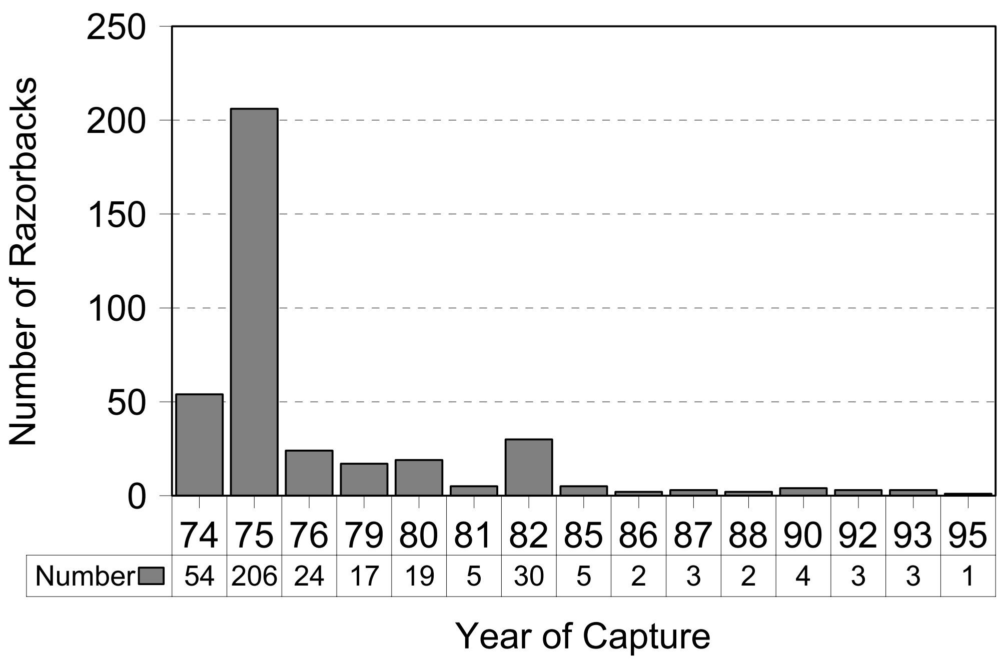

FIGURE 3.15. — Total number of wild razorback suckers (i.e., not stocked fish) collected from the Colorado River near Grand Junction, through 2000. Sampling effort and location varied widely among years, but at least some sampling occurred in all years between 1974 and 2000 except 1977–1978. Razorback suckers were not captured in years that are not depicted. Data were expanded from Figure 12 in Osmundson and Kaeding (1991).

precluded extensive use in the brood-stock program. Forty-five razorback suckers from this pond were equipped with radio transmitters and stocked into the Colorado and Gunnison rivers as part of an experimental stocking; six of those fish were confirmed alive at the end of the 2-yr study (Burdick and Bonar 1997).

Few razorback suckers have been captured downstream from the Grand Valley, between Loma and Lake Powell. Taba et al. (1965) captured eight juveniles in backwaters of the Colorado River downstream of Moab. One adult was captured near Salt Wash (RM 144.2) in 1988 (McAda et al. 1994b). Further downstream, Valdez et al. (1982b) captured two razorback suckers within 2 mi of the confluence with the Green River, and Valdez (1990) captured one more in the same area.

***Gunnison River*. —** Anecdotal accounts indicate that razorback suckers were common in the Gunnison River near Delta in the early and middle portions of the 20th Century (Kidd 1977; Quartarone 1993). However, few specimens have been recorded by knowledgeable collectors. Two specimens from the 1940s are in the University of Michigan Museum of Zoology (reported in Wiltzius 1978). Wiltzius (1978) captured one razorback sucker near Delta in 1975, and Holden et al. (1981) captured three razorback suckers in the same general area in 1981 (Figure 3.14). One of the fish collected by Holden et al. (1981) was a ripe female (P. Holden, personal communication). However, extensive sampling by Valdez et al. (1982a) and Burdick (1995) failed to capture any razorback suckers from the Gunnison River.

With the exception of the fish reported by Taba et al. (1965), no larval or juvenile razorback suckers were captured from the Colorado or Gunnison rivers prior to 2002 (see below).

***Population Augmentation*. —** Although razorback suckers have declined dramatically in abundance in recent years, the Recovery Program considers the Colorado and Gunnison rivers to be suitable habitat for razorback suckers and has begun a reintroduction program to restore populations in the two rivers (Burdick 1992; Nesler 1998; Hudson, et al. 1999).

The Recovery Program is still building a broodstock for future use, but about 19,000 razorback suckers have been stocked into the Gunnison River near Delta and about 44,000 razorbacks have been stocked into the Colorado River upstream from Grand Junction (Burdick 2003; M. Baker, personal communication). Initial surveys indicate that some of the stocked fish are surviving in the Gunnison and Colorado rivers near their stocking location, and others have moved and are surviving further downstream in the Colorado River (Burdick 2003). This reintroduction program is scheduled to continue until a self-sustaining population of about 5,800 individuals is established in the Gunnison and upper Colorado rivers (USFWS 2002d). Some of the stocked razorback suckers have survived to adulthood and spawned successfully — a total of eight larval razorback suckers were captured from the Gunnison River in 2002 (Osmundson 2002b).

Some razorback suckers stocked into the San Juan River have survived (74 out of 5,103 stocked have been recaptured [Ryden 2000b]), grown, and spawned successfully in two different years (two larvae captured in 1998 and seven larvae captured in 1999 [Platania and Brandenburg 2000a, 2000b]), which suggests that augmentation plans for the Colorado and Gunnison rivers will probably produce adult populations in the two rivers. However, ensuring that augmented populations become self sustaining will depend on equal success with the remaining components of the Recovery Program — nonnative fish control, habitat restoration, and instream flow protection.

3.3.2 Habitat Use

Adults and Subadults. — Because few razorback suckers remain in the Colorado River, little habitat-use data are available. Early collections by Kidd (1977) and McAda and Wydoski (1980) were concentrated in gravel-pit ponds connected to the river. The most heavily used pond was in the Walker SWA (near Grand Junction) where razorbacks were collected year round even though they had access to the river at all times. Although the river was sampled much less than the pond, and therefore other habitat types were greatly under represented in those studies, the high number of fish there suggests a preference for that habitat. More recently, Osmundson and Kaeding (1989a) monitored radiotagged razorback suckers in the Colorado River to determine their seasonal habitat-use patterns. Before their study, the gravel-pit pond that had been heavily used by razorback suckers in the 1970s and early 1980s was dramatically altered by high runoff in 1983 and 1984, and razorback sucker use was reduced. In the river, pools and slow runs were the most commonly used habitats on a year-round basis, with highest use occurring from early autumn through late winter (Osmundson and Kaeding 1989a). Backwaters were also used year round, but were most heavily used during spring runoff when use of flooded gravel-pit ponds was also high. The greatest variety of habitats were used in summer when eddies, riffles, fast runs, and shorelines were occupied; however, slow runs were still the most heavily used habitats during that period. Burdick and Bonar (1997) monitored habitat use of radiotagged razorback suckers stocked into the Colorado and Gunnison rivers after rearing in riverside gravel-pit ponds. These fish primarily used the main channel (presumably runs, 47%), backwaters (23%), and eddy-pools (16%). The fish were monitored from March to October, but Burdick and Bonar (1997) did not partition the data by season.

In the Green River, Tyus (1987) reported heavy use of flooded off-channel habitats in spring. Much of this use was in the vicinity of mid-channel spawning bars, and razorback suckers were found in off-channel habitats both before and after the presumed spawning period. During the rest of the year, razorback suckers were most commonly found in mid-channel habitats — shoreline runs in late spring and near mid-channel sand bars in summer. Tyus (1987) did not monitor habitat use in winter.

Ryden (2000b) monitored stocked razorback suckers with radiotelemetry in the San Juan River. Backwaters and other floodplain habitat features are uncommon in the San Juan River, so fish selected other quiet-water habitats during runoff such as eddies and flooded vegetation. Backwaters were used when available. Habitat use during other seasons was similar to the Colorado River, with mostly runs and pools used from autumn through early spring and a variety of quiet and swift water habitats used in summer.

Larvae and Juveniles. **—** The only small razorback suckers reported from the Colorado River were captured by Taba et al. (1965), who found eight juveniles (90–115 mm TL) in "quiet backwater areas" during a 2-yr survey of the river between Moab and Dead Horse Point. That observation is consistent with collections of juveniles from the Green River. Gutermuth et al. (1994) captured two age-0 juveniles in backwaters along the lower Green River in 1991, and Modde (1996) found two in similar habitats in the middle Green River in 1993. Most recently, Modde (1996) found age-0 juveniles in an experimental flooded bottomland (Old Charlie Wash) along the middle Green River when it was drained at the end of the growing season — 28 in 1995 and 45 in 1996.

Early collections for larval razorback suckers were hampered by lack of reliable identification methods as well as a general lack of information on their habitat requirements. However, Tyus (1987) collected larval razorback suckers from quiet shoreline areas downstream from suspected spawning areas as early as 1984. After preliminary investigations to develop appropriate sampling techniques and identify appropriate sampling locations, an intensive study began in the Green River in 1992 to quantify the distribution and relative abundance of larval razorback suckers. During 1992–1996, Muth et al. (1998) collected 1,735 larval razorback suckers from the middle Green River and 440 from the lower Green River. Over the 5-yr study, 95% of the 2,175 larvae collected were found in the flooded mouths of tributaries or other floodplain-type habitats. It is presumed that swim-up larvae emerge from the gravel and are carried by the rising river into floodplain habitats where they remain during the runoff period. Backwaters and floodplains are more productive than the main river channel (summarized by Wydoski and Wick 1998) and provide a warm, food-rich habitat for larvae during this critical period.

Because of the low number of adults in the upper Colorado River, no sampling specifically for larval or juvenile razorback suckers was done prior to 2002, and no wild razorback suckers of either age class were collected during sampling for other purposes. Limited sampling for larval razorback suckers began in the Gunnison River in 2002, and eight larvae were collected (Osmundson 2002b). The larvae were collected from shallow low-velocity habitats along the river margin. Seven larvae were collected in the lower river, but one was captured in the vicinity of floodplain habitat near Delta. Because the larvae may have drifted some distance before they were captured, specific spawning areas have not been determined. Habitat use by young should be the same in the Gunnison and Colorado rivers as in the Green River. Most floodplain habitat in the Gunnison River that could be used by larval and juvenile razorback suckers is near Delta, and most equivalent habitat in the Colorado River is near Grand Junction.

3.3.3 Reproduction

***Timing.* —** Because of the limited number of razorback suckers found in the upper Colorado River, most information comes from other parts of the basin. Ripe female razorback suckers have been found in Lake Mohave, Arizona–Nevada, from December through early June (Minckley et al. 1991), but most spawning occurs in January–April (Minckley 1983; Langhorst and Marsh 1986; Mueller 1989).

Based on capture of ripe fish and subsequent capture of larvae, riverine razorback suckers in the upper basin spawn in spring during increasing and peak snow-melt flows (McAda and Wydoski 1980; Tyus 1987; Tyus and Karp 1990; Muth et al. 1998; Modde and Irving 1998). In the Green River basin, ripe fish have been collected from early April through late June depending on the water year (summarized by Muth et al. 1998). In general, fish spawned earlier in low-runoff years and later in high-runoff years. Most recently, Muth et al. (1998) reported that most spawning in the Green River occurred during mid to late May in the high- water years of 1993, 1995, and 1996 and during April to mid May in the low-water year of 1994. Spawning in the middle Green River occurred at flows ranging from about 2,700 to 22,000 cfs and at water temperatures ranging from 8 to 19.5°C (Muth et al. 1998). Muth et al. (1998) concluded that initiation of spawning generally coincided with a relatively steep and consistent increase in discharge associated with the beginning of spring runoff. However, they believed that spawning was triggered by a suite of interacting environmental cues that was more complicated than the simple interaction of river discharge and water temperature.

The limited data from the Colorado River above Lake Powell agree with the more detailed information from the Green River. Osmundson and Kaeding (1991) summarized razorback sucker data collected by McAda and Wydoski (1980), Valdez et al. (1982b), Osmundson and Kaeding (1989a), and recent USFWS data collected from the Colorado River near Grand Junction and reported that 42 of 157 razorback suckers captured by those investigators were in spawning condition when handled. Of the 42 ripe fish, 40 (95%) were captured between May 24 and June 17 (Figure 3.16). The other two were males and were captured on April 3 and April 10 in a gravel-pit pond connected to the river. The ripe fish were captured over a 15-yr period and relating capture time to status of spring runoff for each fish is difficult. However, peak snow-melt runoff in the Colorado River typically occurs between mid May and mid June (mode, May 31; McAda and Kaeding 1991a) which corresponds with the range of dates reported by Osmundson and Kaeding (1991). The first larvae captured from the Gunnison River were found in late May and early June (Osmundson 2002b), suggesting that they were spawned in early to mid May.

***Habitat.* —** Riverine razorback suckers spawn in riffles or shallow runs over gravel or cobble bars (McAda and Wydoski 1980; Tyus 1987; Tyus and Karp 1990). Water depth and water velocities vary, but are generally relatively shallow (< 1 m) and swift (> 1 ft/s). In the lower basin, razorbacks spawn along gravel beaches of the large reservoirs (Douglas 1952; Minckley 1983; Bozek et al. 1991; Mueller 1989) where wave action prevents accumulation

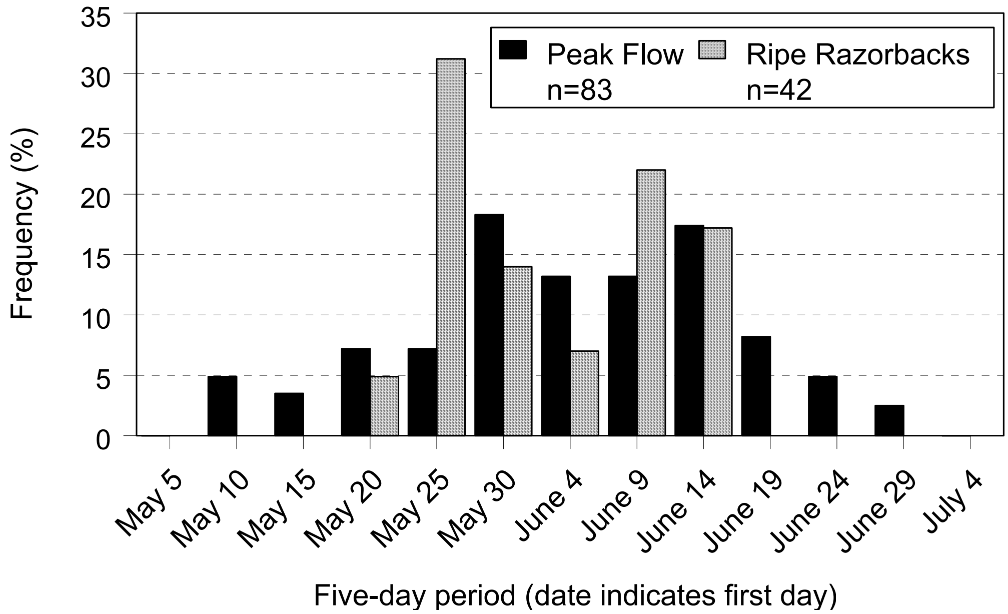

FIGURE 3.16. — Frequency of dates with the highest flow of the year in the Colorado River during 1907–1989 and frequency of capture dates of ripe razorback suckers near Grand Junction. Two ripe male razorback suckers captured in early April, 1975 are not represented. Data are from Figure 13 in Osmundson and Kaeding (1991).

of fine sediments. In the upper basin, most ripe fish have been captured from main-channel habitats, but a few were found in floodplain habitats (Tyus and Karp 1990). In most cases, floodplain habitats were near known spawning bars, and the fish were probably staging in preparation for spawning (Tyus and Karp 1990). However, McAda and Wydoski (1980) captured two ripe females and five ripe males with a single trammel net set in a gravel-pit pond at Walker SWA near Grand Junction. The fish were captured along a shoreline with gravel and cobble substrate. Although direct observations could not be made because of low visibility, the fish were close together in the net and could have been spawning along the shoreline in a manner that has been observed in reservoirs of the lower basin (see below). Also, 38 of the 42 razorback suckers in spawning condition captured in the Grand Valley during 1974–1991 were found in flooded gravel pits (Osmundson and Kaeding 1991).

In the Green River basin, known razorback sucker spawning areas are in the lower 0.5 mi of Yampa Canyon and in the middle Green River near Jensen, Utah (Tyus 1987; Tyus and Karp 1990). Another spawning area is believed to exist in the lower Green River near the mouth of the San Rafael River (Chart et al. 1999). The two uppermost spawning sites are used every year, and individual razorback suckers have been documented using the same sites in two or more years, suggesting some fidelity to individual spawning sites (Tyus and Karp 1990; Modde and Irving 1998). However, Modde and Irving (1998) recently documented individual razorback suckers that occupied both spawning sites in either two different years (four individuals) or within the same year (three individuals). Nonetheless, most recaptured fish have been found at the same spawning site for all captures (Tyus 1987; Tyus and Karp 1990; Modde and Irving 1998). Adult razorback suckers migrate as far as 118 mi to one or the other of the spawning sites during the spawning period (Tyus and Karp 1990).

No specific spawning sites have been identified in the Gunnison or Colorado rivers, but presence of ripe adults and presence of mid-channel cobble bars similar to those used in the lower Yampa and middle Green rivers suggest that most spawning in the Colorado River occurred near Grand Junction. McAda and Wydoski (1980) observed one razorback sucker in a group of spawning flannelmouth suckers over a cobble bar in the Colorado River near Walker SWA. The collection of ripe razorback suckers within the Grand Valley area (Osmundson and Kaeding 1991) provides further evidence that historic spawning areas occurred there. However, the capture of most Colorado River razorback suckers within the Grand Valley suggests that historic spawning migrations were probably short in the upper Colorado River. Osmundson and Kaeding (1989a) documented movements of 7 and 16 mi for two razorback suckers in the Grand Valley during the presumed spawning season; they believed the movements were associated with spawning, but could not confirm it. It is not known whether the few razorback suckers found in the Colorado River near Moab migrated upstream to the Grand Valley or spawned in the lower river similar to the small population found in the lower Green River (Chart et al. 1999).

In the Gunnison River, capture of a ripe female and widespread cobble bars indicate that spawning in that system occurred near Delta. Extensive cobble bars are found between Hartland Diversion Dam and Escalante SWA where the largest remaining piece of floodplain habitat is found. There are about 5 mi of river with potential spawning habitat upstream of Escalante SWA where larvae could hatch and be carried into quiet rearing areas when peak flows are sufficient to provide it. Capture of a single razorback sucker larva in the mouth of Roubideau Creek (downstream end of Escalante SWA) in 2002 (Osmundson 2002b) confirms that stocked razorback suckers spawned in this area.

***Spawning Behavior*. —** Turbid water conditions in the upper basin prevent investigators from observing razorback sucker spawning behavior. However, in the clear-water reservoirs of the lower basin, biologists have observed that female razorback suckers accompanied by two or more males swim around the spawning area, settle to the substrate and deposit their gametes (Douglas 1952; Minckley et al. 1991; Mueller 1989). The fish then moved a short distance and repeated the process. Female razorback suckers do not deposit their full complement of eggs with one spawning effort, and identifiable females have been observed spawning repeatedly over the course of several hours or a day and on successive days within a week (Minckley et al. 1991).

After egg deposition and fertilization, the embryos incubate in the substrate for varying lengths of time depending on water temperature, with time to hatching generally decreasing as water temperature increases (Marsh 1985; Haines 1995). Haines (1995) reported that the mean number of days from fertilization to peak hatch ranged from 6.5 to 12.5 at water temperatures of 12, 16, and 20°C. He also found that hatching success increased with increasing water temperature. Osmundson and Kaeding (1991) suggested that razorback suckers may have spawned in flooded, off-channel habitats that would have been much warmer than main channel habitats during spring runoff. They believed this might explain the dichotomy between increased hatching success at warm water temperatures and the cold water that exists in the main channel when spawning occurs.

In rivers, larvae emerge from the gravel after swim-up and are entrained in the current, which carries many of the young fish into floodplains, backwaters, flooded tributary mouths or other quiet-water habitats for rearing (Tyus and Karp 1990). Timing of spawning (at or approaching the peak of runoff) ensures that these habitats are available to the larvae when they emerge from the substrate. Floodplains, backwaters, and other quiet-water areas are the most productive habitats of the river (Wydoski and Wick 1998) and provide important nursery habitat for young razorback suckers during the first few months of their lives (Tyus 1987; Tyus and Karp 1990; Modde 1996, 1997;Wydoski and Wick 1998; Muth et al. 1998). These habitats are temporary and, with the exception of main-channel backwaters, usually do not last the growing season. Reduced spring flows caused by water development and construction of dikes and levees have reduced the availability of flooded bottomlands.

***Influence of River Flow on Reproductive Success.* —** Razorback suckers are rare in the Gunnison and Colorado rivers, and sampling for larvae has only been done for 1yr. Therefore, no relationships between reproductive success and river flows can be established. However, information on reproductive success from the Green River is available and can be used to predict what would be expected in the Colorado River. Modde et al. (1996) did a mark-recapture population estimate of razorback sucker in the middle Green River that built upon the original estimate by Lanigan and Tyus (1989). Length-frequency distributions of razorback suckers captured by both groups of investigators showed relatively constant size distributions of adults over a 12-yr period (1982–1992) even though recaptured fish exhibited low but measurable annual growth rates (Modde et al. 1996). Small-sized (i.e. young) adults were usually present, and Modde et al. (1996) inferred from this and other data that some, albeit limited, recruitment to the adult population was occurring on an irregular basis. They compared the incidence of young adults with flow conditions in preceding years and found that the number of small fish was positively related to increases in discharge 5 yr preceding capture. Five years is approximately the time that razorback suckers require to mature. The higher discharges associated with subsequent recruitment of young adults supports the conclusions of others that flooded bottomlands (which are most abundant in high discharge years) are important habitats for survival of larval razorback suckers (Tyus and Karp 1990; Modde et al. 1996). Adequate floodplain habitat may assist young razorback suckers to avoid predation by the large number of introduced fishes that have become established in the basin (Modde et al. 1996). Modde et al. (1996) concluded that:

> "Without sufficient flows to reconnect floodplain habitats to the main channel, it is unlikely that razorback sucker recruitment will continue."

Reconnecting the floodplains to the main channel will also play a vital role in reestablishing the razorback sucker population in the Gunnison and upper Colorado rivers.

3.3.4 Growth

Larvae and Juveniles. — Larval razorback suckers hatch at 7–9 mm TL and reach swim-up at 9–11 mm TL, about 13 d after hatching (Marsh 1985; Snyder and Muth 1990). For the first month of life, average daily growth of larvae collected from backwaters and floodplains of the Green River was 0.27–0.33 mm (Muth et al. 1998). Two juvenile razorback suckers captured from backwaters in the lower Green River in July 1991 were 36.6 and 39.3 mm long and were estimated to be 55 and 58 d post hatching (based on otolith analysis; Gutermuth et al. 1994). Young razorbacks that remained in a controlled wetland in the middle Green River (Old Charlie Wash) for an entire growing season (i.e., through October) reached 74–125 mm long (mean, 94 mm) by their first autumn (Modde 1996). Old Charlie Wash provided favorable nursery habitat for the young razorback suckers — warm water and abundant zooplankton which promoted fast growth (Modde 1996).

Over the course of the first growing season, larval razorback suckers in floodplains of the Green River grew two to three times faster than larvae in other types of off-channel habitats (floodplains, mean 0.65–1.1 mm/d; flooded tributary mouths or side channels, mean 0.32 mm/d; Muth et al. 1998). Floodplains in the Gunnison River are primarily terraces, whereas floodplains of the Green River include both terraces and depressions. Although terraces do not remain flooded as long as depressions, they are more productive than tributary mouths and similar flooded habitats (Crowl et al. 1998) and allow for increased growth of larval razorback suckers while they are available.

Increased growth during early life can provide important survival benefits for larval fish, especially if size-dependent processes, such as predation by small, gape-limited predators, are important regulators of larval survival. For example, Bestgen et al. (1997) demonstrated that the predatory effects of adult red shiners on mortality of larval Colorado pikeminnow decreased 5–40% as growth increased by 0.1 mm increments from 0.2 to 0.6 mm/d. Adult red shiners (Ruppert et al. 1993) and fathead minnows (Dunsmoor 1993) also prey on catostomid larvae and fast growth could reduce predation risk by these small fishes.

It is not known whether larval growth in Gunnison River floodplains will be as fast as observed in the Green River, but growth should be faster than in main-channel habitats. If the growth and survival estimates presented above hold for the Gunnison River, 1 d's growth in a floodplain will provide the same survival benefits to a larval razorback sucker as does 3 d's growth in other quiet-water habitats.

Adults and Subadults. — Relatively little information is available on growth of wild razorback suckers between their first year of life and adulthood. However, recapture of stocked razorbacks has provided some information. Based on recapture of razorback suckers stocked into the San Juan River, fish stocked at <350 mm TL gained an average of 0.10 mm/d

(36.5 mm/yr) and fish stocked at >350 mm TL gained an average of 0.03 mm/d (11.0 mm/yr) between stocking and recapture (Ryden 2000b). However, growth was highly variable — one fish doubled in length (251–502 mm TL) and increased from 185 to 1,300 g over 42 months, but another did not grow at all over 12 months (Ryden 2000b). No difference between growth of males and females was noted (Ryden 2000b). Recaptured razorback suckers originally stocked in the Gunnison River grew an average of 0.17 mm/d (62 mm/yr; fish were 199–399 mm TL at stocking and recapture intervals were 3–704 d; Burdick 2000a).

Maximum growth potential of razorback suckers in an ideal environment was demonstrated in a growout pond in the Grand Valley (Osmundson and Kaeding 1989b). Age-0 razorback suckers were stocked into the pond in June 1987 at a mean length of 54.8 mm TL and had reached a mean length of 307 mm by the following November. Mean length increased to 413 mm in autumn 1988 and to 462 mm when the study was terminated in October 1989. The largest fish at the end of the study was 505 mm TL and weighed 1,488 g (Osmundson and Kaeding 1989b). All fish appeared to be sexually mature at the end of the 2.4-yr study. This growth rate appears to be exceptional, at least in part, because stocking rates were very low, food was very abundant, and water temperatures were warm for much of the year. Survival of these fish was also exceptionally high, almost 100% (Osmundson and Kaeding 1989b). Most fish raised in hatchery ponds in the upper basin mature at about 400 mm TL and 4–5 yr (M. Baker, personal communication); but fish begin to mature at 2–3 yr in the warmer water and longer growing season at Dexter National Fish Hatchery (Hamman 1985). Maturation appears to be more dependent on size than age (i.e., fish that grow faster will mature earlier; M. Baker, personal communication). Growth slows dramatically after razorback suckers mature, with recaptured adults from the middle Green River averaging 1.66 mm/yr (Modde et al. 1996).

3.3.5 Summary of seasonal flow-habitat relationships for razorback sucker

Spring**. —** Increasing river flow in spring triggers movement of adults to spawning areas (Table 3.7). Reproduction of razorback sucker is primarily triggered by increasing river discharge and warming water temperatures. Flows sufficient to inundate floodplains are critical to survival and growth of larval razorback sucker (Section 3.2.3). Successful recruitment of razorback sucker in the upper Colorado River basin has only been documented after years with spring flows sufficient to inundate floodplains. The largest remaining floodplain in the Gunnison River occurs at Escalante SWA, and the largest remaining floodplains in the Colorado River occur at scattered locations in the Grand Valley (above and below the mouth of the Gunnison River) and at Scott Matheson WP near Moab.

In addition to providing inundated floodplains, spring flows create and maintain habitats used by razorback suckers year round. High spring flows also are channel-forming flows that maintain channel complexity, scour side channels, and build backwaters. In-channel features created during these high flows provide habitats for all life stages in the remaining seasons of the year. An extended period without channel-forming flows allows extensive silt and sand

TABLE 3.7. — Qualitative relationship between river flow and razorback sucker habitat.

Season	Life Stage	River[a]	Habitat Maintenance Objective
Spring	Adults/ subadults	CO, GU	● Increasing flows associated with the beginning of spring runoff to initiate movements of adults to spawning areas and trigger reproduction.
		CO, GU	● Flows sufficient to inundate floodplain habitats to provide warm, food-rich environments for growth and gonadal maturation and to reestablish river-floodplain connections.
		CO, GU	● Flows sufficient to scour vegetation from river banks and side channels to maintain habitat complexity and provide the suite of habitats used by adults in other seasons.
		CO, GU	● Flows sufficient to scour sediment from cobble/gravel bars and to prevent redeposition of fines during the spawning period
		CO, GU	● Flows sufficient to mobilize the bed on a widespread basis in both runs and riffles; fines are flushed from the substrate and interstitial spaces are increased to maintain benthic productivity for foodweb linkages.
	YOY/ Juveniles	CO, GU	● Flows sufficient to inundate floodplains to provide warm, food-rich environments for growth and survival of larvae immediately after hatching.
		CO	● Flows sufficient to transport sediment and build in-channel sandbars for backwater habitat in summer, autumn, and winter.
		CO, GU	● Flows sufficient to reduce abundance of nonnative fishes (competitors and predators) in backwater habitats used in summer, autumn, and winter.
Late Spring/ Early Summer	Adults/ subadults	CO, GU	● Declining flows that gradually decrease to base flows and allow water temperatures to increase.
		CO, GU	● Flows sufficient to provide a migration corridor for migrating adults and drifting larvae.
Summer/ Autumn	Adults/ subadults	CO, GU	● Stable base flows that maximize preferred habitats and provide sufficient water depth for fish to move among habitats used for foraging and resting.
	YOY	CO, GU	● Stable base flows that maximize the amount of backwater habitats available to YOY and small juveniles.
Winter	Adults/ subadults	CO, GU	● Stable base flows that maximize preferred habitats and provide sufficient water depth for fish to move among habitats used for foraging and resting.
	YOY	CO, GU	● Stable base flows that maximize the amount of backwater habitats available to YOY and small juveniles.

[a] CO = Colorado River; GU = Gunnison River.

deposition that may become stabilized with emergent vegetation. Even higher flows are then required to recreate and maintain these vital habitats.

***Summer–Autumn*. —** Slowly decreasing flows allow small razorback suckers to leave the floodplains and enter the Gunnison and Colorado rivers without being stranded. Young-of-the-year razorback suckers use backwaters and other quiet water habitats after floodplains are no longer available (Section 3.2.2). Adults use a variety of habitats during the summer and autumn, but concentrate their activities in slow runs and pools. Summer and autumn flows should maximize the number and variety of main-channel habitats.

***Winter*. —** Adults use mainly pools and slow runs in the winter. No data are available on habitat use of YOY and small juveniles in the main channel during winter. However, stable base flows that maximize pools, runs, and backwaters should benefit razorback suckers during winter.

3.4 HUMPBACK CHUB

The humpback chub is a mid-sized cyprinid endemic to the Colorado River basin (Minckley 1973). It is one of three closely related species — humpback chub, bonytail, and roundtail chub — that historically occupied the large, mainstem rivers of the basin. Humpback chub was not described as a species until 1946 (Miller 1946), and bonytail was considered to be a subspecies of roundtail chub until 1970 (Holden and Stalnaker 1970). This resulted in considerable taxonomic confusion during early surveys, and early investigators often lumped the species under a common category of chub or bonytail (Holden 1991). Recent researchers have been reluctant to identify some specimens in the field and have referred to individuals with intermediate morphological characters as intergrades or members of the *Gila* complex (e.g., Kaeding et al. 1990; Chart and Lentsch 1999a, 1999b). Recent studies have confirmed the taxonomic validity of the three species (e.g., Rosenfeld and Wilkinson 1989; McElroy and Douglas 1995) and provided field workers with techniques to reliably identify individuals with intermediate morphology without having to sacrifice them for detailed taxonomic analyses (Douglas et al. 1989; Douglas et al. 1998). However, the early taxonomic ambiguity precluded reliable information about the distribution and abundance of humpback chub before water development and introduction of nonnative fishes substantially changed riverine habitat. The loss of habitat in the lower basin, unknown status of the species in the upper basin, and potential for further habitat loss through construction of more reservoirs prompted the species to be included as endangered when the first list of endangered species was published in 1967 (USFWS 1967).

3.4.1 Distribution and Abundance

General. — Humpback chub are currently found in discrete populations, within canyon-bound reaches or other areas of similar habitat (Valdez and Clemmer 1982). The largest population of humpback chub occurs in the Little Colorado and Colorado rivers in Grand Canyon, Arizona. Valdez and Ryel (1995) estimated the mainstem population to be about 3,750 adults, and Douglas and Marsh (1996) estimated the Little Colorado River population to be about 4,346 adults. Considerable movement of adult humpback chubs has been documented, but most spawning occurs in the Little Colorado River (Valdez and Ryel 1995). In the upper Colorado River basin, small populations occur in the Yampa and Green rivers within Dinosaur National Monument (Karp and Tyus 1990a); the Green River in Desolation and Gray canyons (Chart and Lentsch 1999b); and the Colorado River in Black Rocks (Kaeding et al. 1990), Westwater Canyon (Chart and Lentsch 1999a), and Cataract Canyon (Valdez 1990).

Colorado River. — Two populations of humpback chub are found in the upper Colorado River — Black Rocks, a 1-mi long reach just upstream from the Colorado-Utah state line, and Westwater Canyon, an 18-mi long canyon-bound reach of rapids, deep pools, and violent eddies (Figure 3.17). The two populations are generally considered to be distinct because they are separated by about 11 mi, but movement between the two populations has been

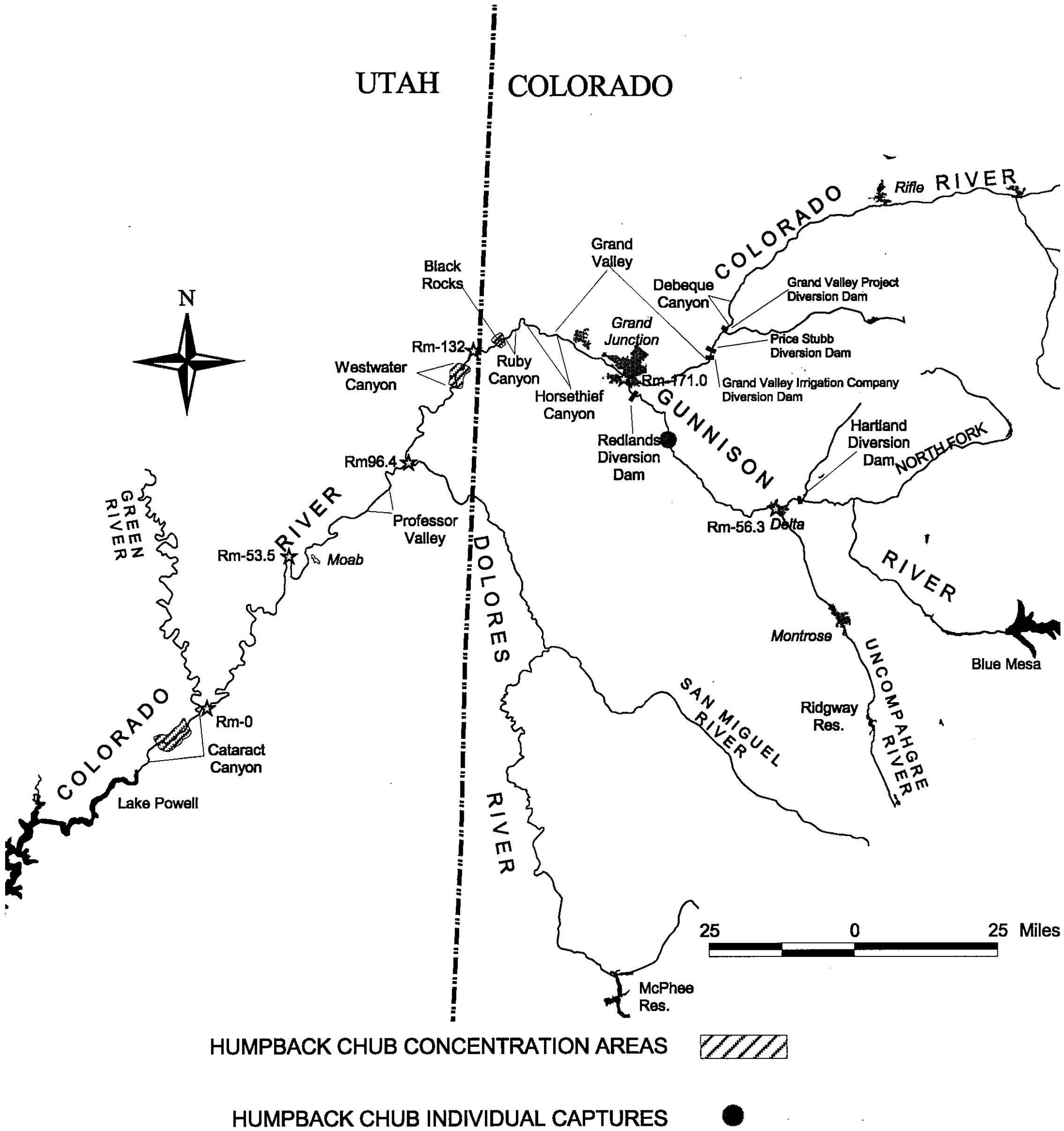

FIGURE 3.17. — Distribution of humpback chub in the upper Colorado and Gunnison rivers.

documented (Valdez and Clemmer 1982; Kaeding et al. 1990; Chart and Lentsch 1999a; McAda 2002b).

Both populations have been sampled regularly since the late 1970s and were generally considered to be stable, with annual reproduction and regular recruitment of young fish to the adult population (Valdez and Clemmer 1982; Kaeding et al. 1990; McAda et al. 1994b; Chart and Lentsch 1999a). However, quantitative population estimates have not been attempted until recently. Chart and Lentsch (1999a) sampled Westwater Canyon during 1993–1996 and made population estimates based on year-to-year recaptures at three discrete sites within the canyon. Sampling was restricted to the three sites because rapids and violent eddies made sampling very difficult in the rest of the canyon. The average annual population estimate for the three sites combined was 6,985 adults (Chart and Lentsch 1999a). A population estimate for the 1998–2000 period is being completed. The average adult population size for Black Rocks during 1998–2000 was estimated to be about 740 individuals (McAda 2002b). Decline in catch rates suggest that the population has decreased, but annual population estimates are not significantly different from each other (McAda 2002b).

Adult humpback chubs in the upper Colorado River are relatively sedentary and generally remain within a small area (Valdez and Clemmer 1982; Kaeding et al. 1990; Chart and Lentsch 1999a). Displacement of radiotagged humpback chubs in Black Rocks averaged 0.5– 0.9 mi (Valdez and Clemmer 1982; Kaeding et al. 1990), and displacement of fish tagged with carlin tags averaged 0.7–1.0 mi (Valdez and Clemmer 1982; Kaeding et al. 1990). Thirty-two percent of the humpback chubs tagged and recaptured by Kaeding et al. (1990) were recaptured at their release site, and 80% were recaptured within 0.3 mi of it. However, they recaptured two humpback chubs that had originally been tagged in Westwater Canyon, about 14 mi downstream. Valdez and Clemmer (1982) also reported movement of a humpback chub from Westwater Canyon upstream to Black Rocks.

The majority (82%) of fish tagged and recaptured by Chart and Lentsch (1999a) in Westwater Canyon showed no net movement, although some fish moved among the three sampling sites. Among others, they recaptured two fish only 2 d after being tagged at Black Rocks. The abrupt downstream movement may have been precipitated by handling stress (Chart and Lentsch 1999a). In addition, seven humpback chubs originally tagged in Westwater Canyon by Chart and Lentsch (1999a) were recaptured in Black Rocks (McAda 2002b). Intervals between tagging and recapture varied from 1 to 6 yr; there is no way to determine how long the fish had been in Black Rocks or how long it took them to move 14 mi upstream. One of these fish was recaptured a second time in Black Rocks 1 yr after its first recapture (C. McAda, unpublished data).

***Gunnison River*. —** The Gunnison River has never been considered habitat for humpback chub. However, Burdick (1995) found one specimen during an intensive survey of the river from Delta to its mouth (Figure 3.17). It was captured in a deep eddy-pool complex within a canyon-bound reach at RM 22.0 and is the only recorded capture of a humpback chub from the Gunnison River. The Black Canyon of the Gunnison contains habitat typical of other canyon-bound areas where humpback chubs are currently found. It is possible that they were eliminated from the Black Canyon after water temperature was reduced by Blue Mesa Reservoir, but the only *Gila* spp. reported during pre-impoundment surveys were roundtail chub (summarized by Wiltzius 1978).

3.4.2 Habitat Use

Adults and Juveniles**.** — In Black Rocks and Westwater Canyon, humpback chubs are usually captured in eddies and similar low-velocity habitats adjacent to the higher velocities of the main channel (Archer et al. 1985; Valdez and Clemmer 1982; Chart and Lentsch 1999a; USFWS, unpublished data). Most fish are captured along the vertical rock walls, in or near deep water. However, adult humpback chubs have also been captured in shallow water along sand and silt shorelines in Black Rocks (C. McAda, personal observation). Habitat use by humpback chubs in Grand Canyon is similar, with most adults occupying large eddies adjacent to the main channel (Valdez and Ryel 1995). As noted above, the lone humpback chub in the Gunnison River was collected in a deep pool-eddy complex in a canyon-bound reach. Seasonal differences in habitat use were not observed in Black Rocks or Westwater Canyon; however, humpback chubs in the Yampa River moved into deep pools during low-flow periods (Karp and Tyus 1990a).

Juvenile humpback chubs in Black Rocks and Westwater Canyon occupy habitats similar to those of adults (Chart and Lentsch 1999a; USFWS, unpublished data). However, juveniles in Grand Canyon are most abundant along talus slopes, debris fans, and vegetated shorelines (Valdez and Ryel 1995; Converse et al. 1998). They moved from low-velocity shoreline habitats to offshore eddies at 175–200 mm TL (Valdez and Ryel 1995).

Young-of-the-Year**.** — Young-of-the-year humpback chubs have been collected from a variety of low-velocity habitats within Westwater Canyon, including shorelines, backwaters, and embayments (Chart and Lentsch 1999a). They used low-velocity habitats as they were available with very little selection of specific habitats (Chart and Lentsch 1999a). In Black Rocks, small humpback chubs were collected from backwaters as well as small, quiet pockets along the steep rock walls (Valdez and Clemmer 1982).

3.4.3 Reproduction

Humpback chubs spawn in late spring or early summer at, or shortly after, the peak of snowmelt runoff (Valdez and Clemmer 1982; Kaeding et al. 1990; Karp and Tyus 1990a; Chart and Lentsch 1999a). Kaeding et al. (1990) reported spawning in Black Rocks at water temperatures ranging from 14 to 24°C based on expressible eggs or sperm. In an earlier study, Valdez and Clemmer (1982) noted tuberculate males in spawning colors at water temperatures of 11.5°C. Sperm could be readily stripped from males, but eggs could not be expressed from females at that time. Ripe females were not collected, but spent females were found about 15 d later suggesting that spawning occurred at water temperatures between 11.5 and 16°C (Valdez and Clemmer 1982).

More recently, Chart and Lentsch (1999a) estimated spawning dates in Westwater Canyon by back-calculation and found that spawning varied from mid June in 1992 and 1994 to late July in 1995. River flow at time of spawning was highly variable among years (range, 11,200 [1992]–20,400 cfs [1996]), but river temperatures were consistently between 19 and 21°C when spawning activity peaked (Figure 3.18). Spawning dates varied because of large differences in spring runoff, with spawning occurring earlier in years with low runoff and later in years with high runoff. Water temperatures were also about 20°C when spawning occurred in Yampa Canyon (Karp and Tyus 1990a).

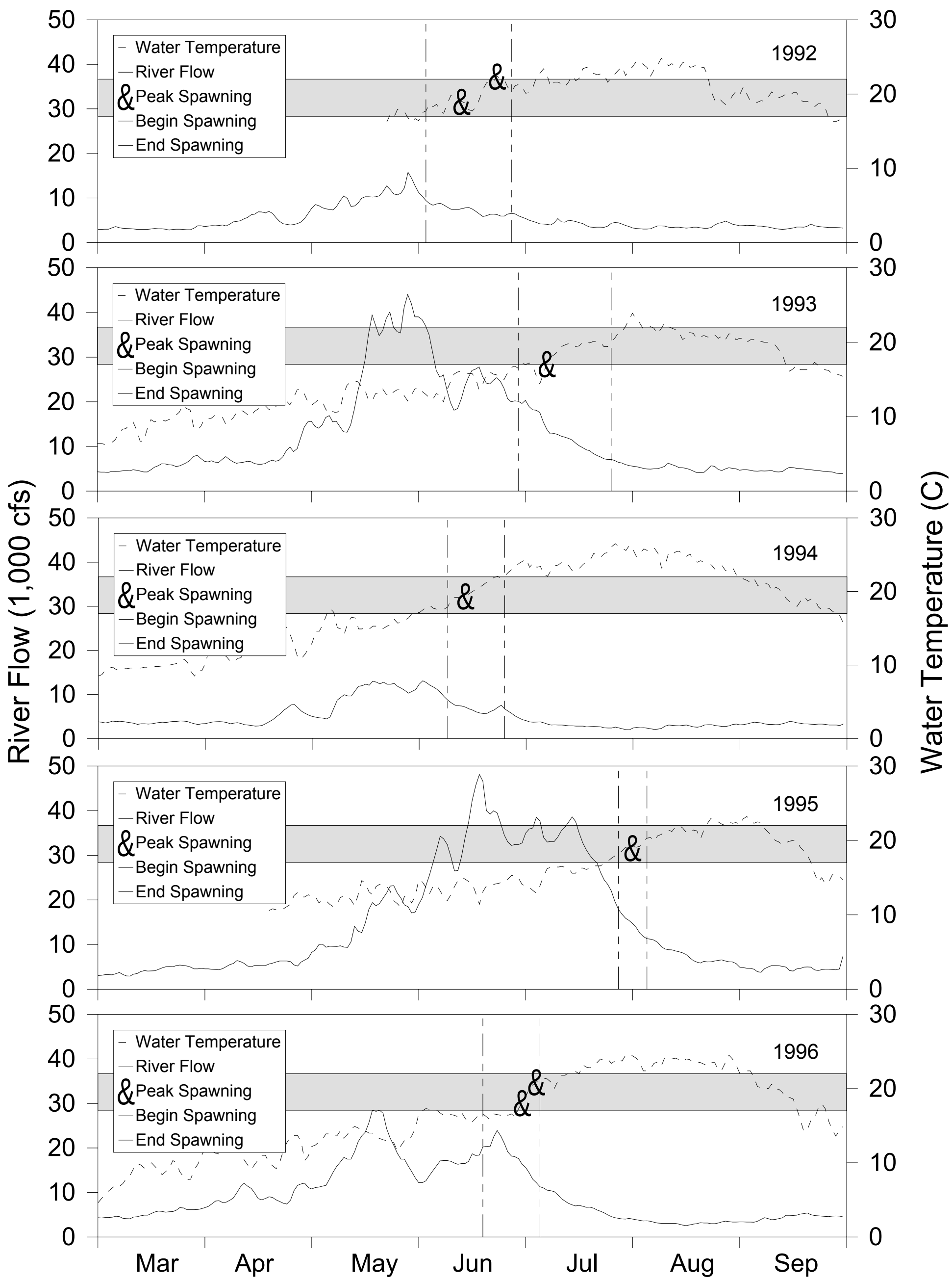

FIGURE 3.18. — Estimated spawning dates (range denoted by vertical lines; peak denoted by ◆) for humpback chubs in Westwater Canyon compared with Colorado River mean-daily flow and maximum-daily water temperature (°C) as measured at the USGS gage near the Colorado-Utah state line, 1992–1996. Data were rearranged from Figure 5 in Chart and Lentsch (1999a); shading denotes water temperatures between 17 and 22°C. Spawning dates were estimated by backcalculating to hatching dates based on total length of age-0 chubs and then subtracting 6 d for incubation. Peak spawning dates were based upon modes of length-frequency distributions; years with two peak spawning dates had bimodal length-frequency distributions.

Very little is known about the spawning behavior of humpback chubs. However, they are broadcast spawners with semi-adhesive eggs that adhere to, or become lodged in, the interstitial spaces of gravel and cobble substrates (Hamman 1982). Humpback chubs in the Little Colorado River spawn in areas of clean gravel associated with complex habitat structure such as large boulders combined with chutes, runs, and eddies (Gorman and Stone 1999). Spawning has not been directly observed in the upper basin, but it likely occurs over clean cobble and gravel bars in habitats similar to those described for the Little Colorado River.

Incubation can range from 19 d at water temperatures of 10°C to 3 d at 26°C (Hamman 1982). Larvae hatch in 5–6 d at water temperatures of 19–20 °C (Hamman 1982), temperatures observed at the peak of spawning in Westwater Canyon (see above). Hatching success and survival of larvae is greatest at water temperatures of 19–22 °C (Hamman 1982; Marsh 1985). Larvae are not generally captured in drift samples and remain near the spawning area (Chart and Lentsch 1999a), but they can be displaced downstream by catastrophic floods (Valdez and Ryel 1995). As noted above, early juvenile humpback chubs are found in the same short reaches inhabited by adults.

Influence of River Flow on Reproductive Success. **—** Chart and Lentsch (1999a) monitored reproductive success of humpback chubs in Westwater Canyon by seining for YOY in July and August in 1992–1996. Catch rates were variable, but they were higher in years of average and greater-than-average runoff than they were in years with below-average runoff. July densities were positively correlated with peak runoff, and August densities showed a positive trend, but the relationship was not significant. Overall, summer density of YOY humpback chubs was highest in Westwater Canyon following moderately high runoff flows (mean flow on the highest day of the year ≈ 30,000 cfs; Chart and Lentsch 1999a).

Little additional information is available from other populations relating reproductive success of humpback chubs to river flows. The relationship between reproductive success and river flow has not been examined for the Black Rocks population. Similar sampling was done in Desolation and Gray Canyons, although it was not specifically targeted at defining flow relationships (Chart and Lentsch 1999b). Nonetheless, there was evidence of strong humpback chub recruitment during the high-water years of 1983–1986, and in the moderate to high years of 1993, 1995, and 1996 (Chart and Lentsch 1999b). However, sampling by Day et al. (1999) in Desolation Canyon failed to identify any relationship between summer YOY density and spring flows.

The specific mechanism for high reproductive success of humpback chubs in years of moderately high and higher peak flows is not known. However, as with Colorado pikeminnow, it may be related to cleaned cobble substrates allowing increased hatching success of eggs. It may also be related to a temporary reduction in the numbers of fish that could prey on, or compete with, the small chubs (Section 3.1.3).

3.4.4 Growth

***Larvae and Young-of-the-Year*. —** Humpback chub larvae are 6–7.5 mm long at hatching and reach mean lengths of about 25 mm after 1 month and 48 mm after 2 months (Hamman 1982). Growth rates for YOY in Westwater Canyon ranged from 4.5 mm/month during August 1995 to 25 mm/month in August 1994 (Chart and Lentsch 1999a). Growth rates were significantly correlated with the number of days water temperature exceeded 20 °C and the lowest growth rate was observed during 1995, a year of extended runoff and cooler than average water temperatures (Chart and Lentsch 1999a).

Overwinter survival of age-0 humpback chubs tended to be higher for larger fish, but the relationship between size and overwinter survival varied among rivers. Chart and Lentsch (1999a) reported high survival for large humpback chubs in Westwater Canyon in winter 1994–1995, but YOY of similar size in Desolation Canyon did not exhibit higher than average survival (Day et al. 1999).

***Adults and Subadults*. —** Based on recapture of marked fish, growth of adult humpback chubs averaged 1.08 mm/month for fish 200–250 mm TL and 1.35 mm/month for fish 250–300 mm TL (Chart and Lentsch 1999a). Based on back-calculations of scale annuli, Valdez (1990) estimated that humpback chubs in Cataract Canyon averaged 50 mm at age 1, 100 mm at age 2, 144 mm at age 3, 200 mm at age 4, 251 mm at age 5, and 355 mm at age 6. Growth rates are probably similar for Westwater Canyon and Black Rocks, but no age-growth analyses have been done. Growth rates for humpback chubs from the mainstem Colorado River within Grand Canyon are greater than observed in the upper Colorado River (Valdez and Ryel 1995).

3.4.5 Summary of Seasonal Flow-Habitat Relationships for Humpback Chub

***Spring*. —** Decreasing spring runoff and increasing water temperatures trigger spawning for humpback chubs (Table 3.8). Most spawning occurs on the descending limb of the hydrograph over a wide range of flows. Specific spawning sites in Black Rocks or Westwater Canyon have not been confirmed, but humpback chubs most likely spawn over clean gravel or cobble bars adjacent to the main channel, as occurs in the Little Colorado River. Spring flows sufficient to scour fine sediments from the spawning gravels are necessary for successful reproduction of humpback chubs; strong year classes of humpback chubs in the Colorado and Green rivers have been associated with years of moderate to high spring runoff. Large, recirculating eddies provide habitat for humpback chubs during spring and in the remainder of the year.

Spring flows also create and maintain habitats used by humpback chubs year round. High spring flows are channel-forming flows that maintain channel complexity and build backwaters. In-channel features created during these high flows provide vital habitats for all life stages in the remaining seasons of the year. An extended period without channel-forming

TABLE 3.8. — Qualitative relationships between river flow and humpback chub habitat.

Season	Life Stage	River[a]	Habitat Maintenance Objective
Spring	Adults/ subadults	CO	● Increasing flows associated with the beginning of spring runoff to cue fish for the upcoming spawning period.
		CO	● Flows sufficient to maintain habitat complexity and provide a variety of habitats used in other seasons.
		CO	● Flows sufficient to scour sediment from cobble/gravel bars in potential spawning areas.
	YOY/ Juveniles	CO	●Flows sufficient to transport sediment and build in-channel sand bars for backwater and embayment habitats in summer, autumn, and winter.
		CO	● Flows sufficient to reduce abundance of nonnative fishes (competitors and predators) in backwater habitats used in summer, autumn, and winter.
Late Spring/ Early Summer	Adults/ subadults	CO	● Declining flows that gradually decrease to base flows and allow water temperatures to increase.
		CO	● Flows sufficient to prevent sedimentation of cobble/gravel bars that could smother eggs or embryos.
Summer/ Autumn	Adults/ subadults	CO	● Stable base flows that maximize preferred habitats and provide sufficient water depth for fish to move among habitats used for foraging and resting.
	YOY	CO	● Stable base flows that maximize the amount of backwaters and embayments available to YOY and small juveniles.
Winter	Adults/ subadults	CO	● Stable base flows that maximize preferred habitats and provide sufficient water depth for fish to move among habitats used for foraging and resting.
	YOY	CO	● Stable base flows that maximize the amount of backwater habitats available to YOY and small juveniles.

[a] CO = Colorado River.

flows allows extensive silt deposition that can become stabilized with emergent vegetation. Even higher flows are then required to recreate and maintain these vital habitats. Flows sufficient to inundate floodplains also flush terrestrial organic matter into the river to serve as energy input into the food chain ultimately utilized by humpback chubs. High spring flows also temporarily reduce abundance of nonnative fishes that may prey on or compete with young humpback chubs. This temporary reduction may provide an opportunity for increased growth and survival of YOY humpback chubs.

Summer – Autumn. — Young humpback chubs use a variety of low-velocity habitats in summer and autumn, including shorelines, backwaters, and eddies. Low-velocity habitats with some structure are preferred. Adults use large eddies or deep river sections during this period. Spring flows should transition gradually to base flows that provide a variety of habitats for all year classes to use.

Winter. — No data are available on winter habitat use of humpback chubs in the upper Colorado River. Stable base flows that maximize habitat utilized in summer and autumn should benefit humpback chubs in winter.

3.5 BONYTAIL

The Bonytail was listed as endangered in 1980 (USFWS 1980b) and is the most imperiled of the four endangered fishes (Maddux et al. 1993). It was formerly widespread and abundant in mainstem rivers (Jordan and Evermann 1896), but only scattered individuals have been reported in recent years. Most recently collected individuals were from reservoirs in the lower basin where remnant populations remain. A total of 32 adults were captured from Lake Mohave from 1974 to 1987, and 16 were reported from Lake Mohave in 1988 and 1989 (summarized by Maddux et al. 1993). The reservoir populations have been supplemented in recent years by stocking bonytails from Dexter National Fish Hatchery that are offspring from adults captured from the reservoir in the late 1970s (Marsh 1996).

Few bonytails have been captured from the upper basin in recent years. Bonytail were common in the Green and Yampa rivers of Dinosaur National Monument shortly after closure of Flaming Gorge Dam (Vanicek and Kramer 1969), but they declined rapidly thereafter. Holden and Stalnaker (1975) captured 36 adults from the same area in 1968–1970, and Holden and Crist (1981) found one adult in 1979, but none have been reported from the area since then (Tyus et al. 1982, 1987). A few specimens were collected from Desolation and Gray Canyons of the Green River in the late 1970s and middle 1980s (Holden 1978; Tyus et al. 1982, 1987).

Few bonytails have been captured from the upper Colorado River since intensive sampling began in the 1970s, even though anecdotal and photographic evidence suggest that they were common in the river early in this century (Quartarone 1993). Valdez et al. (1982b) did not capture bonytails during an intensive 3-yr study of the Colorado River between Rifle and Lake Powell. Kaeding et al. (1986) captured one adult at Black Rocks near the Colorado-Utah state line (Figure 3.19), and Valdez (1990) captured 14 *Gila* spp. from Cataract Canyon that were suspected to be bonytails (1 YOY, 7 juveniles, and 6 adults).

The Recovery Program began a reintroduction program in 1996 and has stocked about 84,600 bonytails into the Colorado River since then (Badame and Hudson 2003). The reintroduction program has just begun and it is too early to determine if it will be successful. However, developing a self-sustaining bonytail population in the upper Colorado River will require accomplishments in all phases of the Recovery Program including nonnative fish control, habitat restoration, and instream flow protection. Recovery goals call for a self-sustaining population of about 4,400 adults in the upper Colorado River (USFWS 2002a).

Because of its extreme rarity, little is known about the habitat requirements of bonytail in the upper Colorado River and a summary of its life history is not provided here. However, all four of the endangered fish evolved together in the Colorado River ecosystem, and flow recommendations based on habitat requirements of the more common species and basic river restoration principals (sensu Stanford et al. 1996) should also benefit bonytail.

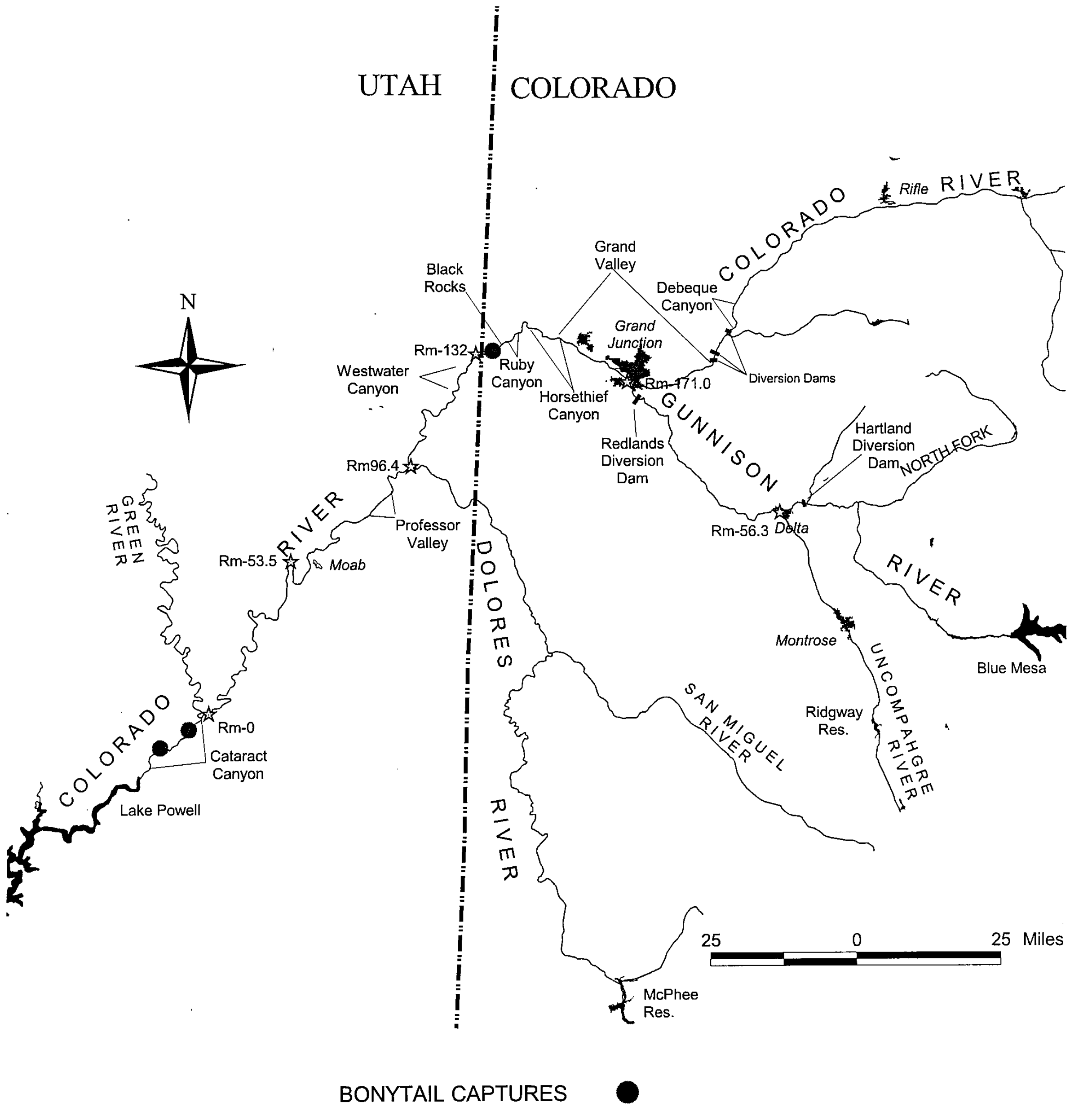

FIGURE 3.19. Recent capture locations of bonytail in the upper Colorado and Gunnison rivers.

4.0 FLOW RECOMMENDATIONS TO BENEFIT ENDANGERED FISHES

A lines-of-evidence approach was used to develop flow recommendations because cause-and-effect experiments to determine biological responses to specific physical changes are difficult to conduct in a large river system. These flow recommendations are based on the best information available concerning the interaction of river flow, geomorphology, and the biological requirements of the four endangered fishes. The flow recommendations should be implemented using an adaptive-management approach that allows for modifications based on information gained as recovery actions for these four species continue.

4.1 Summary of Endangered Fish, River Flow, and Habitat Relationships

This section summarizes the information presented in previous chapters and highlights the information utilized in developing flow recommendations for the Gunnison and Colorado rivers. River flow is the single most important factor in creating and maintaining habitats that are important to the continued survival of the four endangered fishes. Annual and seasonal differences in river flow create and maintain conditions that these species require for all aspects of their life history. Although the four species evolved in the same river system, their habitat requirements vary by species, season, and life stage (Chapter 3). Flow recommendations for the Gunnison and upper Colorado rivers are intended to benefit the species and life stages that occur in each river (Table 4.1).

4.1.1 Colorado pikeminnow

Colorado pikeminnow are found throughout the warm-water reaches of the Colorado and Gunnison rivers, but display differences in distribution by life stage. They are most abundant in the Colorado River, but a small population exists in the Gunnison River. Construction of fish passage at the Redlands Diversion Dam has reconnected the two populations after about 80 years of separation. Most adult Colorado pikeminnow are found in the Grand Valley area of the Colorado River, about 54% of the adult population occupies about 17% of the river that is available to them. Most YOY and juveniles are found in the lower 100 mi of the Colorado River, with highest concentrations of YOY occurring in the lowermost 60 mi.

Adult Colorado pikeminnow occupy warm, off-channel and floodplain habitats for feeding and resting during snowmelt runoff in spring. These habitats provide refuge from high water velocity during spring runoff and have warm temperatures that maximize growth and gonad maturation. Rising spring runoff and the subsequent discharge decline along with increasing water temperature, changing photoperiod, and other factors provide cues that trigger migration and spawning. Spawning begins as river flows decline and river temperatures reach 18–20°C. Larvae hatch after incubating in clean cobble substrates and drift downstream to nursery habitats in low-gradient reaches containing large numbers of backwaters.

TABLE 4.1. — Current known occurrence (K) or potential occurrence (P) with implementation of flow recommendations and other management actions of life stages of endangered fishes in the Gunnison and upper Colorado rivers.

Species and Life Stage	River	
	Gunnison	Colorado
Colorado pikeminnow		
Subadults/adults	K	K
Spawning	K	K
Larvae	K	K
Juveniles		K
Razorback sucker		
Subadults/adults	K	K
Spawning	K	K
Larvae	K	P
Juveniles	P	P
Humpback chub		
Subadults/adults		K
Spawning		K
Larvae		K
Juveniles		K

In summer, stable flows between 3,000–4,000 cfs maximize backwater habitats in lower reaches of the upper Colorado River, but backwaters are available at higher and lower flows. Stable flows and warm temperatures create food-rich backwaters that maximize growth of young fish, which increases the ability of individuals to escape predation or competition. Although rapid growth increases the proportion of young fish in a year class that survive their first year of life, the major factor affecting year-class strength is production of large numbers of young. High abundance of YOY fish ensure that proportionally large numbers of young fish survive their first year of life. Available data indicate that YOY Colorado pikeminnow are most abundant in the Colorado River during years of moderately high spring runoff (about 30,000–40,000 cfs) that had been preceded by years with high spring runoff (>50,000 cfs). High and moderately high spring runoff also temporarily reduces the abundance of three introduced cyprinids that may compete with or eat young Colorado pikeminnow. In contrast, YOY Colorado pikeminnow grow faster and reach larger size in years with low spring runoff.

Adult Colorado pikeminnow prefer areas with braided river channels that provide a suite of habitats for resting and feeding. These complex-habitat areas are created and maintained by spring flows that are high enough to rework cobble bars, scour vegetation, and create new habitats. High spring flows also flush fine sediments from cobble bars and rejuvenate bars used by Colorado pikeminnow for spawning. Flushing fine sediments from the river system also enhances primary and secondary production, which forms the basis for the Colorado River food chain. Although backwaters used as nursery habitats by Colorado pikeminnow are less abundant during years with high runoff, regular scouring flows are critical to long-term maintenance of these habitats.

4.1.2 Razorback Sucker

Adult razorback suckers were found primarily in the floodplain areas of the Colorado River in the Grand Valley and the Gunnison River near Delta. Razorback suckers are rare in both river systems, with few wild individuals captured in recent years. No evidence of successful reproduction was found in either river until 2002 , although ripe (and therefore presumably spawning) razorback suckers were collected in both rivers in the 1980s and 1990s.

A reintroduction program has begun in both rivers and more than 60,000 razorback suckers have been stocked since 1996. Some of these stocked fish have survived, reached maturity, and spawned successfully. Sampling for larval fish was done in the Gunnison River for the first time in 2002, and a total of eight larval razorback suckers were collected. Sampling for larval razorback suckers in the Colorado River is scheduled to begin in 2004.

Adult razorback suckers use floodplains and other off-channel habitats extensively during snowmelt runoff. Spawning is triggered by a suite of environmental factors associated with the peak of spring runoff. Eggs are deposited in mid-channel cobble bars, and larvae drift downstream into quiet, inundated floodplains after hatching. Spawning is timed to coincide with availability of inundated floodplains that provide a warm, food-rich environment for larval razorback suckers. Transport of larval fish into floodplains appears to be the single most important factor in determining successful recruitment by razorback sucker.

Suitable spawning habitat occurs upstream from floodplain areas in both rivers indicating that drifting larvae could enter these critical habitats when water levels are high enough to allow access. The majority of floodplains in the Gunnison and Colorado rivers are terraces. Although terraces do not remain flooded as long as depressions, they are more productive than tributary mouths and similar flooded habitats and allow for increased growth of razorback sucker larvae during the period they are available. Even short periods of fast growth can improve survival of larval fish, especially if size-dependent processes, such as predation by small, gape-limited predators (e.g., red shiner) are important regulators of larval survival.

High spring flows provide access to the floodplains of both river systems. However, the historic frequency, magnitude, and duration of seasonal over-bank flooding in the Gunnison and upper Colorado rivers have been markedly reduced by water development and, in some cases, construction of dikes, levees, and other forms of bank protection. Restoring access to these warm and productive habitats would provide the growth and conditioning environments that are crucial to recovery of self-sustaining razorback sucker populations. High spring flows also produce clean, sediment-free cobble bars (i.e. cobbles with adequate interstitial space) that are critical to egg incubation and survival of larvae.

Adult razorback suckers use a variety of habitats during the rest of the year, but prefer complex river segments. Young razorback suckers use backwaters in much the same way that young Colorado pikeminnow do. Habitats important to all age classes of razorback sucker are created and maintained by high spring flows that maintain the integrity of the river channel.

4.1.3 Humpback Chub

Humpback chubs are found at two locations in the upper Colorado River covered by these flow recommendations — Black Rocks and Westwater Canyon. Humpback chubs remain in these short river segments year-round, but movement between the two populations occurs. Adult humpback chubs primarily use eddies and other quiet habitats along the shorelines and rock faces of deep, swift-water areas. Young humpback chubs use low-velocity shoreline habitats that are more prevalent under base-flow conditions.

Humpback chubs spawn over clean cobble and gravel substrates as peak runoff is decreasing and water temperature is increasing. Larval and YOY humpback chubs are not generally captured in drift samples and they remain within short reaches. Greatest production of YOY humpback chubs in Westwater Canyon was correlated with years of moderately high spring runoff (30,000–40,000 cfs).

4.2 Integration of Biological and Physical Processes

All four endangered species (as well as non-endangered native fishes and other components of the aquatic ecosystem) will benefit from the dynamic processes associated with a more natural river flow regime. These processes maintain in-channel habitats and provide access to floodplains. A more natural flow regime will minimize vegetation encroachment, channel narrowing, and vertical accretion that destroys side-channel habitats. Providing suitable spawning substrates and adequate interstitial spaces for periphyton and aquatic invertebrates — the foundation of the Colorado River food web — also requires maintenance of dynamic sediment processes. These dynamic processes can be achieved with variable annual peak flows at magnitudes, frequencies, and durations mimicking the historical frequency of peak flows.

The fundamental basis of flow recommendations for the Gunnison and upper Colorado rivers reflects general guidelines for river restoration proposed by experts in the field (e.g., Stanford 1994; Stanford et al. 1996; Poff et al. 1997; Richter et al. 1997, Sparks 1997), the quantifiable interaction of river flow and sediment movement (Milhous 1995, 1998; Pitlick et al. 1999; Pitlick and Cress 2000), and habitat relationships and life history requirements of the endangered fish (Chapter 3). The cornerstone of these flow recommendations involve increasing the amplitude (i.e., the relative difference between peak and base flows) of the annual flow regime (Stanford 1994) and incorporating the historic variation among years — thereby mimicking a natural hydrograph. The historic variation in flow regime was driven by variation in annual water availability as snow pack. Therefore, flow recommendations are based on the forecasted volume of water that will be available in the Gunnison and Colorado River basins for the April–July period, which incorporates most of the inflow to the system (Section 4.2.2). In general, flow recommendations are driven by peak flow in spring, with relatively high base flows recommended for years with high spring runoff and relatively low base flows recommended for years with low spring runoff.

Based on the life-history characteristics of the four endangered fishes, river flows that create and maintain important habitats will provide the greatest benefit to the endangered fishes. As summarized by Pitlick et al. (1999):

> "The single most important thing that can be done to maintain habitats used by the endangered fishes is to assure that the sediment supplied to the critical reaches continues to be carried downstream. Sediment that is not carried through will accumulate preferentially in low velocity areas, resulting in further channel simplification and narrowing."

Providing flows sufficient to mobilize the river bed on a regular basis is the best method of ensuring that fine sediments continue to be moved downstream and riverine habitats are maintained. Mimicking a natural hydrograph is a concept that needs to be implemented using specific flow targets that reach or exceed thresholds of sediment movement identified by field research in the rivers where recommendations are made. Pitlick et al. (1999) identified flow levels associated with initial motion ($\mathbf{Q_c}$) and significant motion ($\mathbf{Q_b}$; Section 2.2.2) for the Gunnison and Colorado rivers. These threshold flows form the basis for flow recommendations for the two rivers and recommendations provide for exceeding one or both of these flows for a given number of days, depending on water availability. To ensure that historic variability among years continues to occur, instantaneous peak flows exceeding the two threshold levels are identified in some categories. These peak flows are presented as a range that has occurred during operations since Blue Mesa Reservoir was closed. Peak flows should fall within that range for at least one day when sufficient water is available.

4.2.1 Goal and Objectives of the Flow Recommendations

The goal of these recommendations is to provide the annual and seasonal patterns of flow in the Gunnison River and in the Colorado River downstream from their confluence to enhance populations of the four endangered fishes. The specific objectives were developed to create and maintain the variety of habitats used by all life stages of the four endangered fishes; however, razorback sucker and Colorado pikeminnow are expected to receive the most benefit. Specific objectives include:

- Provide habitats and conditions that enhance gonad maturation and provide environmental cues for spawning movements and reproduction;
- Form low-velocity habitats for adult staging, feeding, and resting areas during snowmelt runoff;

- Inundate floodplains and other off-channel habitats at the appropriate time and for an adequate duration to provide warm, food-rich environments for fish growth and conditioning, and to provide river-floodplain connections for restoration of natural ecosystem processes;

- Restore and maintain in-channel habitats used by all life stages: (1) spawning areas for adults, (2) spring, summer, autumn and winter habitats used by subadults and adults, and (3) nursery areas used by larvae, young of the year, and juveniles; and

- Provide base flows that promote growth and survival of young fish during summer, autumn, and winter.

4.2.2 Hydrologic Categories for Annual Recommendations

Water availability, primarily in the form of winter snow pack, is variable and must be considered when developing and implementing flow recommendations for the two rivers. To understand the annual variation in unregulated inflow to the system, unregulated April–July inflow to the Gunnison River at the USGS gage near Grand Junction (09152500) was summarized for 1937–1997 and the Colorado River at the USGS gage near the Colorado-Utah state line (09163500) for 1958–1997 based on data provided by NRCS (Figure 4.1; Tables A.9 and A.31). This analysis excluded the early part of the century which was exceptionally wet and a short period in the 1930's which was exceptionally dry. Therefore, the relative frequency of water availability for this time period should accurately reflect future conditions in the Colorado and Gunnison basins. April–July water availability during that period ranged from 281,000 af in 1977 to 3,147,000 af in 1984 in the Gunnison River and from 942,000 af in 1977 to 8,904,000 af in 1984 in the Colorado River. NRCS uses data collected between 1961–1990 to predict unregulated inflow for the two rivers based on snow pack measurements. The average for that period is 1,448,000 af for the Gunnison River and 3,726,000 af for the Colorado River. To incorporate natural variation in the river system, flow recommendations are provided for six hydrologic categories based on unregulated April–July inflow to the Colorado River for 1958–1997 and to the Gunnison River for 1937–1997 (Table 4.2, Tables A.9 and A.31):

- **Wet (0–10 % exceedance)**. — A year during which the forecasted April–July runoff volume has been equaled or exceeded in 10% or less of the years since 1937. This hydrologic condition has a 10% probability of occurrence.

- **Moderately Wet (10–30% exceedance)**. — A year during which the forecasted April–July runoff volume has been equaled or exceeded in 10–30% of the years since 1937. This hydrologic condition has a 20% probability of occurrence.

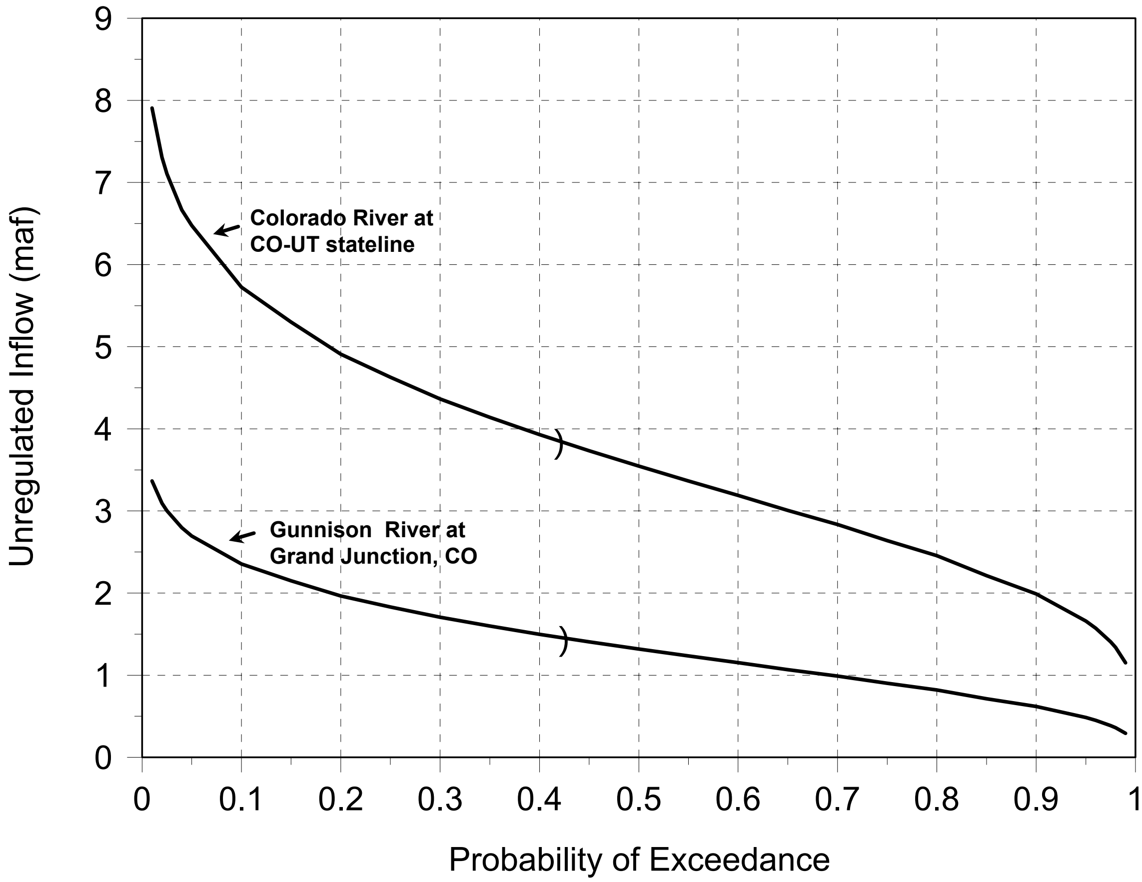

FIGURE 4.1 — Probability of different levels of unregulated April–July inflow to the Gunnison River at the USGS gage near Grand Junction, Colorado (09152500; 1937–1997) and to the Colorado River near the Colorado-Utah state line (09163500; 1958–1997). Closed circles (●) represent means for 1961–1990, which is used by NRCS to compare predicted inflow for April–July every spring — Gunnison River near Grand Junction, 1.448 maf; Colorado River near the state line, 3.726 maf.

- **Average Wet (30–50% exceedance)**. — A year during which the forecasted April–July runoff volume has been equaled or exceeded in 30–50% of the years since 1937. This hydrologic condition has a 20% probability of occurrence.

- **Average Dry (50–70% exceedance)**. — A year during which the forecasted April–July runoff volume has been equaled or exceeded in 30–50% of the years since 1937. This hydrologic category has a 20% probability of occurrence.

TABLE 4.2. — Exceedance levels and water volumes for six hydrologic categories used to determine flow recommendations for the Gunnison and Colorado rivers. Exceedance levels are based on estimated Apri–July unregulated inflow for 1937–1997 for the Gunnison River and 1958–1997 for the Colorado River. Averages are based on 1961–1990.

Hydrologic Category/ Exceedance Level	Gunnison River at Grand Junction		Colorado River near Colorado-Utah state line	
	Water Volume (1,000 af)	Percent of Average (1,448 af)	Water Volume (1,000 af)	Percent of Average (3,726 af)
Wet 0–10%	≥ 2,355	163	≥ 5,725	154
Moderately Wet 10–30%	≥ 1,705 < 2,355	118–163	≥ 4,364 < 5,725	117–154
Average Wet 30–50%	≥ 1,319 < 1,705	91–118	≥ 3,547 < 4,364	95–117
Average Dry 50–70%	≥ 990 < 1,319	68–91	≥ 2,835 < 3,547	76–95
Moderately Dry 70–90%	≥ 621 < 990	43–68	≥ 1,991 < 2,835	53–76
Dry 90–100%	≤ 621	43	≤ 1,991	53

- **Moderately Dry (70–90% exceedance)**. — A year during which the forecasted April–July runoff volume has been equaled or exceeded in 70–90% of the years since 1937. This hydrologic condition has a 20% probability of occurrence.

- **Dry (90–100% exceedance)**. — A year during which the forecasted April–July runoff volume has been equaled or exceeded in 90% or more of the years since 1937. This hydrologic condition has a 10% probability of occurrence.

Flow recommendations for the Gunnison River are based on measurements at the USGS gage near Grand Junction. However, most changes in spring peak flows have occurred as a result of Blue Mesa Reservoir and therefore, any additional water necessary to meet the flow recommendations will probably come from that reservoir. Average April–July inflow to Blue Mesa Reservoir for 1961–1990 is 698,000 af, but extremes for the 1937–1997 period of record ranged from 166,700 af in 1977 to 1,434,000 af in 1984. Water volumes for the six hydrologic categories at Blue Mesa Reservoir (Table A.9) are:

- **Wet**. — ≥ 1,123,000 af (≥161% of average).

- **Moderately Wet**. — ≥871,000 and <1,123,000 af (125–161% of average).

- **Average Wet**. — ≥709,000 and <871,000 (102–125% of average).

- **Average Dry**. — ≥561,000 and <709,000 af (80–102% of average).

- **Moderately Dry**. — ≥381,000 and <561,000 af (55–80% of average).

- **Dry**. — <381,000 af (<55% of average).

The six hydrologic categories were chosen to represent the range of water availability that could be expected in the future. In reality, annual runoff volume is a continuous variable rather than corresponding to six discrete categories. However, predictions of runoff volume are usually considerably less than 100% accurate and using six categories rather than discrete variables corresponding to specific inflow volumes as the basis for flow recommendations allows for management flexibility while still reaching specific target flows. The target flows identified for each hydrologic category perform specific tasks (e.g., flush fine materials from riffles or pools, or inundate specific areas of floodplain) that restore or maintain habitat for the endangered fishes in the Gunnison and Colorado rivers. Gunnison River flows make important contributions to flow recommendations in the Colorado River downstream from their confluence.

4.2.3 Basis for Level and Duration of Annual Spring-Peak Target Flows.

Specific spring-peak flow targets were developed from Pitlick et al. (1999) based on their intensive study of the Gunnison and Colorado rivers (Section 2.2.2). Based on their field observations of processes and rates of change in the two rivers, they recognized that:

> “Flows equal to or greater than ½ the bankfull discharge are needed to mobilize gravel and cobble particles on a widespread basis, and to prevent fine sediment from accumulating in the bed....Flows greater than ½ the bankfull discharge thus provide several important geomorphic functions, assuming they occur with sufficient regularity.”

> “Flows equal to bankfull discharge are also important because they fully mobilize the bed and thereby maintain the existing bankfull hydraulic geometry.”

Pitlick et al. (1999) recommended that to maintain habitat conditions in the Gunnison and Colorado rivers, ½ bankfull and bankfull flows should occur with a long-term average equal to what occurred during 1978–1997. They further recommended that to improve habitat conditions in both rivers, the two threshold flows should occur with a long-term average equal to what occurred during 1993–1997.

As described in Section 2.2.2, median values for ½ bankfull (**Q_c**) and bankfull (**Q_b**)flows for the Gunnison River are 8,070 and 14,350 cfs, respectively. Table 4.3 summarizes the cumulative number of days that the two threshold flows were exceeded during 1978–1997 (maintain conditions) and Table 4.4 summarizes the number of days they were exceeded during 1993–1997 (improve conditions). Based on these calculations, Pitlick et al.'s (1999) recommendation to **maintain habitat conditions** would mean that over the long term, flows should exceed 8,070 cfs for an average of 20 d/yr and flows should exceed 14,350 cfs for an average of 4 d/yr. Their recommendation to **improve habitat conditions** requires that, over the long term, flows should exceed 8,070 cfs for an average of 32 d/yr and flows should exceed 14,350 cfs for an average of 7 d/yr.

Using the long-term averages presented in Tables 4.3 and 4.4, Table 4.5 presents flow recommendations for the Gunnison River based on the six hydrological categories described in Section 4.2.2. There are many possible scenarios by which spring-peak flow recommendations for the Gunnison River could have been derived from Pitlick et al. (1999). Table 4.5 presents one of these using the two target flows described above (**Q_c** and **Q_b**). Because water availability varies considerably over time, target flows and durations were varied among the six hydrological categories to develop the long-term averages recommended by Pitlick et al. (1999). Using ½ bankfull and bankfull flows as the primary targets means that most of the variation occurs in the recommended duration for the different flows — longer durations for hydrological categories with the greatest amount of water. Targets are identified as greater than or equal to the two threshold levels, with duration identified as ranges. The first number in a column refers to the number days needed to maintain habitat conditions and the second column (identified in bold) refers to the number of days needed to improve habitat conditions. The range of days is intended to give river managers flexibility to implement the flow recommendations within the hydrological categories. To provide for variation among years, a range of instantanteous peak flows greater than median bankfull flows are also recommended for the two wettest categories. These instantanteous peaks have occurred within these categories since Blue Mesa Reservoir was closed. When sufficient water is available to do so, the highest peak should fall within this range for at least one day. A range of instantaneous peak flows other than the target flows are also indicated for the two driest categories to provide a one-day target when river managers do not have to reach ½ median bankfull discharge and sufficient water is available to do so. These flows have also occurred in the Gunnison River within these categories since Blue Mesa Reservoir was closed.

TABLE 4.3. — Gunnison River near Grand Junction (USGS 09152500): days per year that spring flows exceeded median ½ bankfull discharge (Q_c = 8,070 cfs) and median (Q_b = 14,350 cfs), 1978–1997.

Hydrologic Category	Year	Days ≥ 8,070 cfs	Days ≥14,350 cfs
Wet	1983	54	15
	1984	59	29
	1985	57	2
	1993	50	18
	1995	74	16
	Category Average	58.8	16
Moderately Wet	1979	19	0
	1980	31	0
	1986	18	0
	1987	8	0
	1997	38	0
	Category Average	22.8	0
Average Wet	1978	0	0
	1982	0	0
Average Dry	1991	0	0
	1992	0	0
	1996	0	0
Moderately Dry	1988	0	0
	1989	0	0
	1990	0	0
	1994	0	0
Dry	1981	0	0
Grand Average	-	20.4	4

TABLE 4.4 — Gunnison River near Grand Junction (USGS 09152500): days per year that spring flows exceeded median ½ bankfull discharge (Q_c = 8,070 cfs) and median (Q_b = 14,350 cfs), 1993–1997.

Hydrologic Category	Year	Days ≥ 8,070 cfs	Days ≥14,350 cfs
Wet	1993 1995	50 74	18 16
	Category Average	62	17
Moderately Wet	1997	38	0
Average Wet	-	-	-
Average Dry	1996	0	0
Moderately Dry	1994	0	0
Dry	-	-	-
Grand Average	-	32	7

TABLE 4.5. — Spring peak-flow recommendations for the Gunnison River near Grand Junction (USGS 09152500)[a]: number of days per year the flows should exceed ½ bankfull discharge (Q_c = 8,070 cfs) and bankfull discharge (Q_b = 14,350 cfs).

Hydrologic Category	Expected Occurrence	Flow Target and Duration [b]		Instantaneous Peak Flow (cfs)
		Days/Year ≥ 8,070 cfs	Days/Year ≥ 14,350 cfs	
Wet	10%	60–**100**	15 – **25**	15,000–23,000 [d]
Moderately Wet	20%	40–**60**	10 – **20**	14,350–16,000 [d]
Average Wet	20%	20–**25**	2 – **3**	≥14,350 [e]
Average Dry	20%	10–**15**	0 – **0**	≥8,070 [e]
Moderately Dry	20%	0–**10**	0 – **0**	≥2,600 [f]
Dry	10%	0–**0**	0 – **0**	~900–4,000 [g]
Long-Term Weighted Average [c]		20 – **32**	4 – **7**	

[a] This table represents one possible way of achieving the long-term weighted average for sediment transport.
[b] Lower value in each range is for maintenance, higher (bold) value in each range is for improvement.
[c] Weighted values equal days/year x expected occurrence (the sum of all weighted average values equals the long-term weighted average in days/year).
[d] Instantaneous peak flows within this range have occurred in these hydrological categories since Blue Mesa Reservoir was closed. These observed instantaneous peaks are desired in the future in conjunction with meeting the flow targets. No specific peak flow within this range is recommended to ensure continued variability among years..
[e] Expected minimum peak flow when recommendations are met; actual peak may exceed this value, ensuring continued variability among years.
[f] Instantaneous peak flow that has occurred since Blue Mesa Reservoir was closed. Peak flows are expected to equal or exceed this level in years when $\mathbf{Q_c}$ is not reached.
[g] Range of peak flows within this category that have occurred since Blue Mesa Reservoir was closed. Lowest number reflects base flow. Peak flows are expected to continue to occur within this range; no specific flow within this range is recommended, ensuring variability among years.

Pitlick et al.'s (1999) recommendations also applied to the Colorado River. Median values for ½ bankfull discharge are similar for reaches upstream and downstream from Westwater Canyon (18,500 and 20,000 cfs, respectively), but median values for bankfull discharge vary substantially between the two reaches (35,000 and 58,600 cfs) largely because channel cross-sectional area is substantially wider in the reach below Westwater Canyon. Flows greater than 58,000 cfs occurred in only 9 out of 87 years of the gage record near Cisco — twice since 1978 (1983, 1984), the 2 wettest years during that period, and not at all in some very wet years (e.g., 1985, 1993, 1995). Pitlick and Cress (2000) believed transport levels equal to significant motion occurred at flows less than bankfull discharge, in the lower portion of the Colorado River, but were unable to quantify that relationship. Because of this uncertainty, recommendations were made for the Colorado-Utah state line gage (09163500) where measurements of bankfull discharge are more reliable. The median values for ½ bankfull and bankfull discharges in the river reaches represented by the state line gage are 18,500 and 35,000 cfs, respectively. Table 4.6 summarizes the number of days per year that median ½ bankfull and median bankfull flows were exceeded during the 1978–1997 period (to maintain conditions). Table 4.7 provides a similar summary during the 1993–1997 period (to improve habitat conditions). Based on these calculations, Pitlick et al.'s (1999) recommendation to **maintain habitat conditions** would mean that, over the long term, flows should exceed 18,500 cfs for an average of 28 d/yr and flows should exceed 35,000 cfs for an average of 7 d/yr (Table 4.6). Their recommendation to **improve habitat conditions** requires that, over the long term, flows should exceed 18,500 cfs for an average of 39 d/yr and flows should exceed 35,000 cfs for an average of 9 d/yr (Table 4.7).

Using the long-term averages presented in Tables 4.6 and 4.7, Table 4.8 presents spring-peak flow recommendations for the Colorado River based on the six hydrological categories described in Section 4.2.2. There are many possible scenarios by which spring-peak flow recommendations for the Colorado River could have been derived from Pitlick et al. (1999). Table 4.8 presents one of these using the two target flows described above ($\mathbf{Q_c}$ and $\mathbf{Q_b}$). Because water availability varies considerably over time, target flows and durations were varied among the six hydrological categories to develop the long-term averages recommended by Pitlick et al. (1999). Using ½ bankfull and bankfull flows as the primary targets means that most of the variation occurs in the recommended duration for the different flows — longer durations for hydrological categories with the greatest amount of water. Targets are identified as greater than or equal to the two threshold levels, with duration identified as ranges. The first number in a column refers to the number days needed to maintain habitat conditions and the second column (identified in bold) refers to the number of days needed to improve habitat conditions. The range of days is intended to give river managers flexibility to implement the flow recommendations within the hydrological categories. As with the Gunnison river, a range of instantanteous peak flows greater than median bankfull flows are also recommended for the two wettest categories to increase among-year variability. Peak flows should be within this range when water availability is sufficient to do so. These instantanteous peaks have occurred within these categories since Blue Mesa Reservoir was closed. A range of

TABLE 4.6. — Colorado River near Colorado-Utah state line (USGS 09163500): days per year that spring flows exceeded median ½ bankfull discharge (Q_c = 18,500 cfs) and median bankfull discharge (Q_b = 35,000 cfs), 1978–1997.

Hydrologic Category	Year	Days ≥ 18,500 cfs	Days ≥35,000 cfs
Wet	1983	60	32
	1984	69	53
	1985	68	10
	1995	67	21
	Category Average	66	29
Moderately Wet	1979	45	2
	1980	44	0
	1986	57	0
	1993	48	18
	1997	56	7
	Category Average	50	5.4
Average Wet	1978	17	0
	1982	2	0
	1996	22	0
	Category Average	13.7	0
Average Dry	1987	6	0
	1991	1	0
	Category Average	3.5	0
Moderately Dry	1988	0	0
	1989	0	0
	1992	0	0
	1994	0	0
Dry	1981	0	0
	1990	0	0
Grand Average		28.1	7.2

instantaneous peak flows other than the target flows are also indicated for the two driest categories to give a target when river managers do not have to reach ½ median bankfull discharge. These flows have also occurred in the Colorado River since Blue Mesa Reservoir was closed.

TABLE 4.7 — Colorado River near Colorado-Utah state line (USGS 09163500): days per year that spring flows exceeded median ½ bankfull discharge (Q_c = 18,500 cfs) and median bankfull discharge (Q_b = 35,000 cfs), 1993–1997.

Hydrologic Category	Year	Days ≥ 18,500 cfs	Days ≥35,000 cfs
Wet	1993	48	18
Moderately Wet	1995 1997	67 56	21 7
	Category Average	61.5	14
Average Wet	1996	22	0
Average Dry	-	-	-
Moderately Dry	1994	0	0
Dry	-	-	-
Grand Average	-	38.6	9.2

TABLE 4.8. — Spring peak-flow recommendations for the Colorado River near the Colorado–Utah state line (USGS 09163500)[a]: number of days per year the flows should exceed ½ bankfull discharge (Q_c = 18,500 cfs) and bankfull discharge (Q_b = 35,000 cfs).

Hydrologic Category	Expected Occurrence	Flow Target and Duration [b]		Instantaneous Peak Flow (cfs)
		Days/Year ≥ 18,500 cfs	Days/Year ≥ 35,000 cfs	
Wet	10%	80–**100**	30–**35**	39,300–69,800 [d]
Moderately Wet	20%	50–**65**	15–**18**	35,000–37,500 [e]
Average Wet	20%	30–**40**	6–**10**	≥35,000 [f]
Average Dry	20%	20–**30**	0	18,500–26,600 [e]
Moderately Dry	20%	0–**10**	0	9,970–27,300 [g]
Dry	10%	0	0	5,000–12,100 [g]
Long-Term Weighted Average [c]		28–**39**	7.2–**9.1**	

[a] This table represents one possible way of achieving the long-term weighted average for sediment transport.
[b] Lower value in each range is for maintenance, higher (bold) value in each range is for improvement.
[c] Weighted values equal days/year x expected occurrence (the sum of all weighted average values equals the long-term weighted average in days/year).
[d] Instantaneous peak flows within this range have occurred in these hydrological categories since Blue Mesa Reservoir was closed. These observed instantaneous peaks are desired in the future in conjunction with meeting the flow targets. No specific peak flow is recommended to ensure continued variability among years.
[e] Lower number reflects the expected minimum peak flow when recommendations are met and the upper number reflects peak flows that have occurred since Blue Mesa Reservoir was closed. Peak flow is expected to occur within this range, but no specific value is provided to ensure variability among years.
[f] Expected peak flow when flow recommendations are met. Actual peak may exceed this level ensuring variability among years.
[g] Range of peak flows that have occurred since Blue Mesa Reservoir was closed. Peak flows are expected to continue to fall within this range when $\mathbf{Q_c}$ is not reached. No specific recommendation within this range is made to ensure variability among years.

4.3 Flow Recommendations for the Gunnison River

The following information reiterates the spring peak-flow recommendations described in Table 4.5 and places them in context with the amount of in-channel habitat maintenance that is expected to occur. Recommended base-flow conditions for the summer, autumn, and winter periods are also described to provide habitat for the endangered fishes throughout the year.

4.3.1 Spring Peaks

Spring peak flows are the defining flows of a river system and do most of the work to maintain habitat for the endangered fishes. Releases from the Aspinall Unit to assist in meeting these target flows should gradually increase and decrease according to established ramping rates (300–500 cfs/d at releases <5,000 cfs and 10% per day at releases >5,000 cfs). However, see section 4.5.2 for uncertainties related to ramping rates. To the extent possible, maximum Aspinall Unit releases should be timed to correspond with maximum river flows in the North Fork of the Gunnison River to provide maximum benefit to the Gunnison River within critical habitat. Although timing of peak flows in the North Fork (measured at the USGS gage near Somerset, 09132500) and the Gunnison River did not always coincide before the Aspinall Unit was constructed, highest mean-daily flows of the year for both rivers fell within 2 d of each other 75% of the time during 1937–1965. To correspond with the historical hydrograph, peak flows in the Gunnison River should occur between May 15 and June 15 each spring.

Specific flow recommendations for six hydrologic categories are presented below and summarized in Table 4.9. These flows correspond to the Pitlick et al. (1999) recommendations for channel maintenance. There are no specific flow recommendations for floodplain habitat; however, the benefits are described when floodplain habitat is expected to be created.

Dry. — Flows equal to ½ bankfull or bankfull discharge are not required in this category. However, instantaneous peak flows ranging between about 900 cfs (base flow) and 4,000 cfs have occurred in this category since Blue Mesa Reservoir was closed. Instantaneous peak flows should be in that range when water availability is sufficient. There will be no channel maintenance occurring in this category. However, the rising and falling river associated with even a small peak will provide environmental cues that the endangered fishes use for spawning. Because considerable extra water would be required to reach river levels associated with initial motion, it is not warranted to provide that extra water during dry years. Releases from the Aspinall Unit should correspond to historical spring release patterns with no extra water released for the endangered fishes. Water for the endangered fishes should be stored for release during the summer migration period to provide access to the Redlands Fishway (Section 2.1.2). No flooded bottomland habitat is provided at this flow.

TABLE 4.9. — **Flow recommendations for the Gunnison River; measured at the USGS gage near Grand Junction (09152500).**

Hydrologic Category	Magnitude and Duration	Discussion/Anticipated Effect
		Spring Peak Flow[a]
Dry; 90–100% exceedance	1-d peak of 900–4,000 cfs	No in-channel scouring of gravel or cobble bars is anticipated at this flow; however, fine material on the surface will be moved and further deposition will be slowed. No flooded bottomland habitats will be provided, but some inundation of tributary mouths will occur. The small peak will provide spawning cues for Colorado pikeminnow and razorback sucker.
Moderately Dry; 70–90% exceedance	≥8,070 cfs ($\mathbf{Q_c}$) 0–10 d 1-d peak when $\mathbf{Q_c}$ not reached, ≥2,600 cfs	In-channel maintenance will not occur unless initial motion is reached for at least one day; however, fine material on the surface will be moved and further deposition will be slowed. The limited peak will provide spawning cues for Colorado pikeminnow and razorback sucker. No flooded bottomland habitat will be provided, but some inundation of tributary mouths will occur, providing some warm, quiet water habitats for growth and gonad maturation of endangered fish.
Average Dry; 50–70% exceedance	≥8,070 cfs ($\mathbf{Q_c}$) 10–15 d Peak flow should at least equal $\mathbf{Q_c}$	The median level for initial motion will be reached, providing some cleansing of gravel and cobble bars. This will prepare spawning habitat for Colorado pikeminnow and increase primary and secondary production. Floodplain inundation will begin, but habitat will be limited; however, some warm, quiet-water habitats will be available for growth and gonad maturation of razorback sucker and Colorado pikeminnow.
Average Wet; 30–50% exceedance	≥8,070 cfs ($\mathbf{Q_c}$) 20–25 d ≥14,350 cfs ($\mathbf{Q_b}$) 2–3 d Peak flow should at least equal $\mathbf{Q_b}$	The median level for significant motion is reached or exceeded in in the river. Widespread cleansing of gravel and cobble bars is accomplished. In-channel habitats used by endangered fish will be maintained in important river reaches; channel narrowing will be slowed or prevented. Floodplain habitats will be widespread (about 80 ac will be available at Escalante SWA at flows greater than 8,000 cfs), but duration of widespread flooding will be brief. Quiet water habitats will be available for use by adult endangered fish. Wide-spread areas with clean substrates should provide habitat needed for maximum reproductive success of Colorado pikeminnow and increased primary and secondary production.
Moderately Wet; 10–30% exceedance	≥8,070 cfs ($\mathbf{Q_c}$) 40–60 d ≥14,350 cfs ($\mathbf{Q_b}$) 10–20 d 1-d peak of 14,350–16,000 cfs	The median level for significant motion is reached or exceeded in the river, creating and maintaining important habitats for Colorado pikeminnow and razorback sucker in large areas of the river. Gravel is flushed from pools, creating important wintering habitat for both species. Floodplains are extensive for a brief period (about 200 ac at Escalante SWA at 14,000 cfs); river flows exceeding 8,000 cfs will provide floodplain habitat at Escalante SWA and surrounding areas to provide quiet, warmwater habitat for growth and survival of larval razorback sucker. Wide-spread areas with clean substrates should provide habitat needed for maximum reproductive success of Colorado pikeminnow and increased primary and secondary production.

TABLE 4.9. Continued.

Hydrologic Category	Magnitude and Duration	Discussion/Anticipated Effect
Spring Peak Flow, (Continued)		
Wet; 0–10% exceedance	≥8,070 cfs (**Q_c**) 60–100 d ≥14,350 cfs (**Q_b**) 15–25 d 1-d peak of 15,000–23,000 cfs	The median level for significant motion is reached or exceeded in the river, creating and maintaining important habitats for Colorado pikeminnow and razorback sucker in large areas of the river. Braided channels are maintained, creating complex areas with a variety of habitats. Gravel is flushed from pools, creating critical wintering habitat for both species. Floodplains are extensive for two weeks (about 200 ac at Escalante SWA at 14,000 cfs); river flows exceeding 8,000 cfs will provide floodplain habitat at Escalante SWA and surrounding areas for an extended period to provide quiet, warmwater habitat for growth and survival of larval razorback sucker.
Summer Through Winter Base Flow		
Dry; 90–100% exceedance	≥750– ≥1,050 cfs	Flows should gradually decline from peak runoff, but a minimum of 1,050 cfs should be provided during the adult migration and larval drift periods from about June through July (Dry) or August (Moderately Dry). This flow provides access to and from the fish passage at Redlands Diversion Dam and provides pool and slow-run habitats through out the Gunnison River. During periods of drought, river flows may decrease below 1,050 cfs after spawning migrations and larval drift are completed, but only after careful analysis of water availability and consultation with Service biologists. Flows downstream from Redlands Diversion Dam should decline by no more than 100 cfs/d during the transition between 1,050 cfs and the target flow. Movement to and from the Redlands Diversion Dam will be significantly restricted, and pool and slow run habitats will be limited below the dam. However, endangered fish restrict movements in autumn and winter, and adequate pool and slow run habitat (preferred winter habitat for Colorado pikeminnow and razorback sucker) is available in other reaches. Gradually reducing flows will allow endangered fish to leave the 2.5-mi reach and prevent stranding. Base flows should be maintained as a minimum until initiation of runoff the following year.
Moderately Dry; 70–90% exceedance	≥750– ≥1,050 cfs	
Average Dry; 50–70% exceedance	>1,050–2,000 cfs	Flows should gradually decline from peak runoff to the target flows by about August (Average Dry and Average Wet) or September (Moderately Wet and Wet). Access to fish passage at Redlands Diversion Dam is provided during migration periods. Further, adequate flows are available to provide year-round habitat in the 2.5 mi of the Gunnison River downstream from the Dam. A wide range of habitats are available in the entire Gunnison River when flows fall within the target ranges. Stable flows provide warm, quiet-water habitats along the shorelines of the river. Base flows should be maintained as a minimum until initiation of runoff the following year.
Average Wet; 30–50% exceedance		
Moderately Wet; 10–30% exceedance	1,500–2,500 cfs	
Wet; 0–10% exceedance		

[a] See Table 4.5

Moderately Dry. — Flows equal to, or greater than, 8,070 cfs are recommended to occur between 0 and 10 d in this category. Over the long term, flows exceeding 8,070 cfs should occur in at least some years that fall into this category in order to improve conditions according to Pitlick et al's (1999) guidelines. Flows should reach at least 2,600 cfs in years when ½ bankfull discharge is not reached and sufficient water is available. Very little in-channel habitat maintenance will occur unless flows exceed 8,070 cfs. No floodplain habitat will be provided in this category. However, the rising and falling river associated with even a small peak will provide environmental cues that the endangered fishes use for spawning.

Average Dry. — Flows should reach 8,070 cfs for 10 to 15 d. Median initial motion is reached that will provide some cleaning of cobble and gravel bars in the majority of the river. Productive bottomlands downstream from Delta begin to flood at this level, but habitat is still limited. Most of the flooded habitat at this level is upstream from Escalante SWA, but about 80 ac of flooded habitat will occur there as well. However, duration of these productive habitats will be short at this flow.

Average Wet. — River flows should equal or exceed 8,070 cfs for 20 to 25 d and should equal or exceed 14,350 cfs for 2 to 3 d. Median significant motion for the Gunnison River is reached at 14,350 cfs. Removing fine sediments from pools and runs will provide appropriate substrates for maximization of primary and secondary production in these dominant habitats. It also ensures that adequate pool habitat is available for adult Colorado pikeminnow and razorback sucker during the rest of the year. Milhous (1998) recommended that river-wide flushing should occur 50% of the time, which corresponds to this hydrologic category.

Flooded bottomlands become important at this level, with flooded habitats developing at several locations between Delta and Escalante SWA. About 200 ac of flooded bottomland is available in Escalante SWA at 14,000 cfs. Total flooded acreage there could be increased to about 240 ac by removing a dike that prevents water from entering some low-lying areas. Other flooded habitats will exist at this flow, but the total surface area of habitat is not quantified at sites other than Escalante SWA. Duration of large areas of floodplain habitat will be short, but will provide opportunity for adult Colorado pikeminnow and razorback suckers to utilize the quiet water habitat to feed and rest out of the main river channel. Floodplain duration will probably not be sufficient to benefit larval razorback suckers except in flooded tributary mouths or other smaller habitats along the river margins.

Moderately Wet. — Flows should equal or exceed 8,070 cfs for 40 to 60 d and should equal or exceed 14,350 cfs for 10 to 20 d in this category. Widespread channel maintenance should occur at these levels, maintaining pool and side channel habitats and cleansing cobble and gravel bars throughout the river. To ensure natural variability among years within this category, a 1-d peak flow should be between 14,350 and 16,000 cfs (reached within this category since Blue Mesa Reservoir was closed) when sufficient water is available to do so.

Flooded bottomland habitat increases to about 260 ac in Escalante SWA at a river flow of 16,000 cfs. With a peak flow of this magnitude, duration of floodplain habitats will be sufficient to provide productive habitats for YOY razorback suckers long enough for them to get a good start on growth before reentering the river when flows subside. Exceeding 8,070 cfs for 40 d should provide flooded habitat long enough to benefit larval razorback sucker at Escalante SWA. Flooded bottomlands will also occur at other sites along the Gunnison River, but total surface area at these sites is not quantified.

Wet. — River flows should exceed 8,070 cfs for 60 to 100 d and should exceed 14,350 cfs for 15 to 25 d. This will provide widespread channel maintenance in the Gunnison River. To ensure natural variability among years, the 1-d peak flow should fall between 15,000 and 23,000 cfs when sufficient water is available to do so; peak flows have fallen within this range since Blue Mesa Reservoir was closed. Flooded bottomland habitat should be widely available at Escalante SWA and at other locations near Delta. The duration of flows greater than 8,070 cfs should provide quiet, warm-water long enough to provide considerable benefits to support growth of larval razorback suckers.

4.3.2 Base Flows

Base-flow recommendations for the different hydrologic conditions are presented in Table 4.9 as ranges of flows over the summer, autumn, and winter. The base-flow period begins after spring runoff is completed and continues through initiation of spring runoff the following year, depending on inflow to the Gunnison River basin. Flows should remain within the ranges specified, but the upper and lower limits are not intended to be targets. Natural variation occurred within the base-flow period and should be used to direct flows based on water availability. The range of allowable flows is not intended to restrict natural variation. Further, the onset of the base-flow period varied considerably — beginning as early as late June in dry years or as late as September or October in wet years. Therefore, base-flow recommendations are presented for different time periods depending on hydrological category. No specific recommendations are presented for the transition between recommended peak flows and the recommended base flows. Flows during the transition period will be largely dependent on declining flows in the tributaries to the Gunnison River. Any modifications in releases from Crystal Reservoir should conform to currently accepted ramping rates (300–500 cfs/d at flows ≤5,000 cfs and 10% per day at flows >5,000 cfs). However, see Section 4.5.2 for uncertainties related to ramping rates.

Although base flows may vary among years and hydrologic conditions, a minimum flow of at least 1,050 cfs should be maintained at the USGS gage near Grand Junction during summer, autumn, and winter in all but dry and moderately dry years. This flow approximates the lowest flow measured by McAda and Fenton (1998) — 981 cfs — and maximizes the amount of pool habitat in the Gunnison River. Pools are preferred habitat for adult Colorado pikeminnow and razorback sucker (Sections 3.2.2 and 3.3.2). Also, flows exceeding 950 cfs prevent fine sediments from settling in riffles which might smother eggs and larvae of endangered fishes (Section 2.2.2).

A flow of 1,050 cfs also roughly corresponds to providing a minimum of 300 cfs downstream from Redlands Diversion Dam (based on a senior water right of 750 cfs) and provides access for migrating fish to the fishway that was recently built there (Sections 2.1.2 and 3.2.1).

During dry and moderately dry years, flows may decrease below 1,050 cfs after the Colorado pikeminnow migration period when doing so would enhance the chances of supplementing peak flows in the upcoming spring and/or providing minimum flows of 300 cfs below Redlands Diversion Dam during the following migration period. However, this reduction should only occur after careful analysis of available water supplies and consultation with Service biologists. Based on estimates extrapolated from McAda and Fenton (1998), pools and slow runs will still be adequate to provide some habitat for Colorado pikeminnow and razorback sucker in the Gunnison River upstream from Redlands Diversion Dam. However, the 2.5-mi reach downstream from Redlands Diversion Dam would experience severe dewatering at this level and endangered fish would be forced to leave this short reach of critical habitat. When possible, flows should decline by $\leq$100 cfs/d during this transition period to prevent stranding endangered fish in the reach. Endangered fish will be able to find adequate wintering habitat downstream in the Colorado River during these extreme conditions. Duration of flows <1,050 cfs should be kept to an absolute minimum, and monitoring should be done to evaluate the effects of these extremely low flows.

The base-flow recommendations are based on the same hydrological categories as recommendations for peak flows. However, it is recognized that water availability may change as the seasons progress depending on precipitation. Adjustments may be necessary if water availability changes dramatically during the base-flow period based on input from a technical team to be formed to implement these recommendations (Section 4.6). During dry and moderately dry years, base flows may persist through late winter and early spring. Recommendations allow for increasing flows during that period, but the target for base flows should continue to be met. During extremely dry years (as occurred in 2002), the technical team should consider water availability and make decisions on when flows downstream from Redlands fishway are most important; water may need to be conserved for critical migration periods. Downstream flows may be reduced, or even stopped briefly, to ensure that at least some water is available when needed. Specific recommendations for the different hydrologic categories appear in Table 4.9.

4.4 Flow Recommendations for the Colorado River Downstream from the Gunnison River

The following information reiterates the spring peak-flow recommendations described in Table 4.8 and places them in context with the amount of in-channel habitat maintenance that is expected to occur. Recommended base-flow conditions for the summer, autumn, and winter periods are also described to provide habitat for the endangered fishes throughout the year.

4.4.1 Spring Peaks

As described in Section 4.2.3, peak flows for the Colorado River are measured at the USGS river gage near the Colorado-Utah state line. Flows from the Gunnison River will contribute a substantial volume of water to peak flows in the Colorado River, but it is unlikely that peak flows from both the Gunnison and Colorado rivers will match exactly. Aspinall Unit releases should occur between May 15 and June 15 and be timed to match peak flows in the North Fork of the Gunnison River to contribute the maximum volume possible to the Colorado River. Specific flow recommendations for each hydrologic category are presented below and summarized in Table 4.10. These flows correspond to the Pitlick et al. (1999) recommendations for channel maintenance. There are no specific flow recommendations for floodplain habitat; however, the benefits are described when floodplain habitat is expected to be created.

The Colorado River immediately upstream from the confluence with the Gunnison River (15-mile reach) is currently operating under a programmatic biological opinion (PBO) that allows for additional water development in the upper subbasin provided that progress is made toward recovery of the four endangered fishes. The PBO provides for coordinated operation of upstream reservoirs to assist in meeting flow recommendations made for the 15-mile reach. Ultimately, flows in the lower reaches of the upper Colorado River will depend on the combination of modified flows in the Gunnison River and flows currently provided for under the PBO. Until there is more definitive evidence as to where and how much water is needed for recovery, recommendations at the Colorado-Utah state line should not be used to override agreements already in place for the upper Colorado River.

Dry. — Flows equal to ½ bankfull or bankfull discharge are not required in this category. However, instantaneous peak flows ranging between 5,000 cfs and 12,100 cfs have occurred in this category since Blue Mesa Reservoir was closed. Instantaneous peak flows should be in that range when water availability is sufficient. This 1-d peak will ensure natural variation among years. Flows of this level will do very little to maintain in-channel habitats; however, the rising and falling river associated with even a small peak will provide some of the environmental cues that endangered fish use to prepare for spawning. No flooded bottomland habitat will be provided anywhere in the river.

Moderately Dry. — Flows equal to or greater than 18,500 cfs ($\mathbf{Q_c}$;½ median bankfull discharge) are recommended to occur between 0–10 d in years falling into this category. Peak flows should exceed this level during at least some years to ensure that habitat is improved according to the recommendations by Pitlick et al (1999). Peak flows have ranged between 9,970–27,300 cfs since Blue Mesa Reservoir was completed and should continue to fall within this range for at least 1 d when water availability is sufficient to do so. Peak flow should be at least 9,970 cfs when median ½ bankfull flow cannot be reached. No channel maintenance will be accomplished unless ½ bankfull flow is reached. No flooded bottomland habitat is provided anywhere in the river, but some quiet-water habitats will be provided in flooded tributary mouths to provide warmer water for gonad maturation of endangered fish. The backwater area at Walker SWA will provide a limited amount of flooded habitat.

TABLE 4.10. — Flow recommendations for the Colorado River; measured at the USGS gage near the Colorado Utah state line(09163500).

Hydrologic Category	Magnitude and Duration	Discussion/Anticipated Effect
		Spring Peak Flow[a]
Dry; 90–100% exceedance	1-d peak of 5,000–12,100 cfs	No channel maintenance will occur in this category. No flooded bottomlands will be provided, but some inundation of tributary mouths may occur. However, a small peak will provide spawning cues for Colorado pikeminnow, razorback sucker, and humpback chub.
Moderately Dry; 70–90% exceedance	1-d peak of 9,970–27,300 cfs ≥18,500 cfs (**Q_c**) 0–10 d	No channel maintenance will occur unless the threshold flow of 18,500 cfs is reached. However, the threshold flow should be reached during at least some years within this category in order to improve main channel habitats (Pitlick et.al. 1999). Some warm quiet-water habitats will be provided for growth and gonad maturation of endangered fish. The backwater at Walker SWA will provide some of this quiet habitat.
Average Dry; 50–70% exceedance	≥18,500 cfs (**Q_c**) 20–30 d 1-d peak of 18,500–26,600 cfs	Initial motion is reached so some in-channel scouring of gravel and cobble bars will occur. Areas with clean substrates for egg deposition and incubation should provide habitat needed for reproduction of Colorado pikeminnow, razorback sucker, and humpback chub, and increased primary and secondary production. Significant motion is not reached, so maintenance of major habitat features within the channel (e.g. pools, runs) will be limited. Some floodplain inundation will occur, therefore, some warm, quiet-water habitats will be available early in the year for growth and gonad maturation of razorback sucker and Colorado pikeminnow.
Average Wet; 30–50% exceedance	≥18,500 cfs (**Q_c**) 30–40 d ≥35,000 cfs (**Q_b**) 6–10 d 1-d peak of ≥35,000 cfs	Significant motion is reached, therefore, in-channel habitats used by endangered fish will be maintained in important river reaches; channel narrowing will be slowed or prevented. Flooding in and around Walker SWA will provide important floodplain habitats, but the extent of available habitat is not known. Widespread areas with clean substrate should provide habitat needed for maximum reproductive success of Colorado pikeminnow, razorback sucker and humpback chub, and increased primary and secondary production.
Moderately Wet; 10–30% exceedance	≥18,500 cfs (**Q_c**) 50–65 d ≥35,000 cfs (**Q_b**) 15–18 d 1-d peak of 35,000–37,000 cfs	Significant motion is reached, creating and maintaining important habitats for Colorado pikeminnow and razorback sucker in wide areas of the river. Floodplain habitats will be extensive, but the surface area of those habitats is not quantified The duration of flows greater than 35,000 cfs will ensure that floodplains are available to improve growth and survival of YOY razorback suckers.

TABLE 4.10. — Continued

Hydrologic Category	Magnitude and Duration	Discussion/Anticipated Effect
	Spring Peak Flow (Continued)	
Wet: 10% exceedance	≥18,500 cfs ($\mathbf{Q_c}$) 80–100 d ≥35,000 cfs ($\mathbf{Q_b}$) 30–35 d 1-d peak of 39,300–69,800 cfs	Median significant motions is exceeded in the Colorado River for an extensive time period, creating and maintaining important habitats for Colorado pikeminnow and razorback sucker in wide areas of the river. Vegetation encroachment will be halted and reversed in wide areas of the river. Floodplain habitats will be extensive, but surface area of those habitats is not quantified. The duration of flows exceeding significant motion will ensure that YOY razorback sucker will be able to utilize floodplain habitats for sufficient time to increase their growth and survival.
	Summer Through Winter Base Flow	
Dry; 90–100% exceedance	≥1,800 cfs	Backwaters for YOY Colorado pikeminnow will be available, but not at maximum number or surface area. Low stable flows will provide for maximum growth of YOY Colorado pikeminnow.
Moderately Dry; 70–90% exceedance	2,500–4,000 cfs	Backwaters in nursery areas should be maximized in both quantity and surface area. Stable flows will provide for constant habitats and maximum warming of water for growth of Colorado pikeminnow. Stable flows will also provide a variety of in-channel habitats for use by juveniles and adults of all endangered species. Pools and slow run habitats will be maximized for winter use of Colorado pikeminnow and razorback sucker. Pools and eddy habitats will be maximized in canyon reaches for humpback chub.
Average Dry; 50–70% exceedance		
Average Wet; 30–50% exceedance	3,000–4,800 cfs	
Moderately Wet; 10–30% exceedance		
Wet: 10% exceedance	3,000–6,000 cfs	Backwaters will be fewer and smaller than at lower flows, but they will still be available for YOY Colorado pikeminnow to use.

[a] See Table 4.8.

Average Dry. — River flows should reach or exceed 18,500 cfs for 20 to 30 d in this category. To ensure variability among years within this category, the highest 1-d peak flow should fall within the 18,500 to 26,600 cfs range when sufficient water is available. In-channel scouring of gravel and cobble bars will begin in much of the river. If flows approach

26,600 cfs, scouring will be widespread and large areas of clean substrates for egg deposition and incubation should provide for maximum reproductive success of Colorado pikeminnow and increased primary and secondary production. Floodplain innundation will increase, but will be limited in duration. However, warm, quiet-water habitats will be available early in the year for growth and gonad maturation of razorback suckers and Colorado pikeminnow.

Average Wet. — River flows should reach or exceed 18,500 cfs for 30 to 40 d and should exceed 35,000 cfs for 6 to 10 d. At these flows, the median level for significant motion will be exceeded and scouring of cobble and gravel bars will be widespread. Scouring of pools, runs and side channels will occur, maintaining in channel habitats for adult Colorado pikeminnow and razorback sucker. Clean cobble and gravel substrates should provide for maximum reproduction of Colorado pikeminnow and increased primary and secondary productivity. Flooding in and around Walker SWA will provide important floodplain habitats, but the extent of available habitat is not known. Duration of flooding will be short, but should give larval razorback sucker a spurt of growth before they leave the floodplain and enter the main channel.

Moderately Wet. — River flows should exceed 18,500 cfs for a total of 50 to 65 d and should exceed 35,000 cfs for 15 to 18 d. To ensure variability among years, the 1-d peak flow should be between 35,000 and 37,500 cfs when water availability is sufficient. The median level for significant motion will be exceeded throughout the river, creating and maintaining important habitats for Colorado pikeminnow and razorback sucker in wide areas of the river. Floodplain habitats will be extensive, but the surface area of those habitats is not quantified. However, quiet, warmwater habitats should be available in sufficient area and duration to improve growth and survival of larval razorback sucker.

Wet. — River flows should exceed 18,500 cfs for 80 to 100 d and should exceed 35,000 cfs for 30 to35 d. Instantaneous peak flows should be between 39,300 and 69,800 cfs, which is the range of peak flows that have occurred since Blue Mesa Reservoir was closed. To ensure variability among years, the 1-d peak flow should be within that range when water availability is sufficient. The long duration at flows exceeding significant motion will ensure that extensive channel maintenance occurs throughout the Colorado River. Vegetation encroachment will be reduced and pools, runs, and side channels will be reworked. Complex river-channel segments that provide important habitats for Colorado pikeminnow and razorback sucker will be created and maintained. Floodplain habitats will be extensive (although unquantified) and will be available for sufficient duration to benefit growth and survival of larval razorback suckers.

4.4.2 Base Flows

Base-flow recommendations for the different hydrologic conditions are presented in Table 4.10 as ranges of flows over the summer, autumn, and winter. The base-flow period begins after spring runoff is completed and continues through initiation of spring runoff the following year, depending on inflow to the upper Colorado River subbasin. Flows should remain within the bounds specified, but the upper and lower limits are not intended to be targets. Natural variation occurred within the base-flow period, and the range of allowable flows is not intended to restrict that variation. Further, the onset of the base-flow period varied considerably — beginning as early as late June in dry years or as late as September or October in wet years. Therefore, base-flow recommendations are presented for different time periods depending on hydrological category. No specific recommendations are presented for the transition between recommended peak flows and the recommended base flows. Flows during the transition period will be largely dependent on declining flows in the many tributaries to the Colorado River.

4.5 Uncertainties

4.5.1 Biological Uncertainties

These flow recommendations were developed using the best information available. However, much remains to be learned about the four endangered fishes and their habitat requirements; recovery of the endangered fishes will require more than simply implementing a set of recommended flows. For that reason, the recommended flows should be implemented using adaptive management and should be accompanied by monitoring programs that evaluate the physical response of the two rivers and the biological response of the endangered fishes to the modified flow regime.

The Recovery Program has implemented other management actions that must also be successful before these species can recover to levels sufficient to sustain themselves through the 21st Century. Razorback suckers and bonytails must be stocked before modifications to the flow regime will benefit either species. Restoration of floodplain function to the Gunnison and Colorado rivers is inferred to benefit recruitment of razorback sucker based on information from the Green River. However, adult populations must be reestablished before that hypothesis can be tested in the upper Colorado River subbasin. The first stocked razorback suckers have reached sexual maturity and have spawned successfully in the Gunnison River; fish stocked more recently will be maturing over the next few years, which will allow assessment of the role of floodplains in successful recruitment for the upper Colorado River subbasin. Within the Gunnison River basin, quantitative assessment (i.e., detailed surveys) of floodplain availability at different flow levels is limited to Escalante SWA, although qualitative surveys have also been done. More detailed surveys of floodable areas in the rest of the basin should be done. Bonytail must be reestablished before anything can be learned about their habitat requirements.

The Recovery Program includes a floodplain restoration element that is designed to acquire and restore flooded bottomland habitat throughout the range of the endangered fishes, including the Gunnison River basin. Presently, only a few properties have been acquired or opened up in the basin; however, more acquisitions are expected. The Recovery Program recently funded a study to determine floodplain needs for recovery of razorback sucker. A model is being developed to identify the total acreage needed for survival and growth of larval razorback suckers. This model will assist the Recovery Program in developing priorities to assist with restoration of floodplain habitat. In addition, management plans are being developed for floodplains already within the public domain. These plans will identify flows necessary to provide appropriate habitat and identify management actions that will assist with inundation of habitats without specific releases for floodplain habitat.

The positive relationships between reproductive success of Colorado pikeminnow and humpback chub and peak river flows are based on limited data. The response of these species to the modified flow regime should be assessed. Nonnative fishes that compete with or prey on their young are temporarily reduced following high spring flows, but populations rebound quickly when low-water years occur. Management actions to reduce population size of nonnative fishes through mechanical means have been initiated, but detrimental effects of nonnative fishes must be reduced before full benefits of the recommended flow regime can be realized.

Although partial restoration of floodplain function through mimicking a natural hydrograph is hypothesized to benefit the endangered fishes, it may also benefit some nonnative fishes. Studies are underway to evaluate nonnative fish response to floodplain restoration. Results of these studies will guide the Recovery Program as it continues the floodplain restoration program.

The relationship between fine sediments and primary and secondary production in the two rivers needs to be further assessed. Long-term studies need to be conducted to evaluate response of periphyton, macroinvertebrates, and other small organisms to a flow regime with a higher frequency of flushing flows. These organisms form the basis of the riverine food web and it remains to be determined whether food availability is limiting abundance of endangered fishes in any or all of the upper Colorado River system.

Riffles have the highest productivity of any individual habitat in the river system, but they are very limited in distribution and abundance. Because of their overwhelming abundance, runs provide the greatest amount of primary productivity. Flushing thresholds for the two habitats are very different and it is important that both habitats are maintained. There is evidence that riffles are cleaned of fine sediments during declining flows as gradient steepens over the bar (e.g., Miller et al. 2002, Harvey et al. 1993). However, much of this material may be deposited in low-velocity areas downstream as gradient drops. Fine sediment buildup in the downstream runs will also have a detrimental impact there. All researchers recognize that periodic channel-wide flushing of cobble bars is necessary to maintain habitat; however, the frequency that is required is unknown. Nonetheless, there is no doubt that extended periods without channel-wide flushing allows sediments to buildup in quiet-water habitats (e.g., backwaters) and allows vegetation encroachment to occur. The Recovery Program has funded a study to prioritize research needs relative to creation and maintenance of physical habitats within the large rivers of the upper basin. The results of this study will assist the program in developing additional research to answer some of these questions. Future work in the Gunnison and Colorado rivers may allow adjustment of these flow recommendations.

All four endangered fishes have long generation times and complicated life histories. Long time periods will be required for their populations to respond to the modified flow regime and other management actions implemented by the Recovery Program. Long-term monitoring programs for all life stages of the endangered fishes should be developed to evaluate their response to all management actions. Management actions, including the recommended flow regime, may need to be modified as more information is accumulated and response of the endangered fishes is assessed.

Recovery goals have been developed for the four endangered fish. Populations in the Gunnison (razorback sucker and Colorado pikeminnow) and Colorado (razorback sucker, Colorado pikeminnow, humpback chub, and bonytail) rivers are identified as playing an important role in recovery of these fish, but the amount of habitat (both quantity and quality) necessary to ensure recovery under ESA remains to be determined. Response of the different populations to management actions will ultimately determine which river is most important for recovery of the different species or populations.

4.5.2 Physical Uncertainties

The relationships among initial motion, significant motion, and river flow are well defined for the Colorado and Gunnison rivers. However, the duration of flows necessary to accomplish in-channel and out-of-channel habitat maintenance objectives is not known. Historical runoff patterns were used to establish duration of the recommended target flows based on the post-Aspinall Unit period. This period was wetter than the long term average for 1937 to 1997, which was used to predict the future occurrence of hydrological categories. As a result, the recommended durations require a large volume of water that may not always be available. Specific studies to define the role of flow duration in creating and maintaining in-channel habitats should be conducted.

These flow recommendations were developed based on reaching target flows that accomplish increasing levels of channel maintenance with increasing levels of water availability (i.e., snow pack). However, an analysis of the Gunnison River's ability to meet the potentially conflicting demands of water use within the basin and river flows necessary to maintain endangered-fish habitat remains to be done. Reclamation is constructing a daily streamflow model that will accomplish this task, but a complete analysis of the Aspinall Unit and the rest of the Gunnison River's ability to contribute to the recommended flow regime remains to be completed. Water availability may limit the ability of the Gunnison River to meet the flow recommendations under certain conditions.

This report contains flow recommendations for both the Gunnison and Colorado rivers. Flow recommendations for the Gunnison River are specifically intended to benefit the Gunnison River, although its flows contribute substantially to flows recommended for the Colorado River as well. Obviously, flows from the Colorado River upstream from their confluence will also be necessary to meet these recommendations. Flow recommendations for both rivers are based on available water as measured by snow pack. During the period 1937–1992, water availability in both rivers fell within the same hydrologic category 80% of the time, but differences occurred. Because of timing and other differences in runoff patterns of the two rivers, it is difficult to predict the effects of flow changes in the Gunnison River on flow patterns of the Colorado River at the Utah-Colorado state line.

High flows that provide channel maintenance and create floodplain habitat need to be assessed for potential impacts to human activities in the Gunnison River basin. Flow recommendations for the wet hydrological category may cause flooding problems at various locations in the basin, particularly near Delta. This issue will be addressed in the Environmental Impact Statement; management activities may be necessary to mitigate potential problems.

Ramping rates currently in place at Crystal Reservoir are based on angler safety and trout habitat in the Gunnison River downstream of the Aspinall Unit. No direct relationship between these ramping rates and endangered fish impacts or benefits have been established for the Gunnison River. Current ramping rates should be examined to determine if modifications could be made to benefit the endangered fishes.

Another uncertainty concerns reserved water rights currently held by Black Canyon National Park in the Gunnison River immediately downstream from the Aspinall Unit. The Park Service is currently quantifying those water rights, but final determination of the size of the right under Colorado water law may not occur for some time. The Park Service's filing is intended to maintain physical habitat in the Gunnison River within the National Park and proposes flow patterns similar to those recommended in this report — increased frequency of flushing flows in spring and lower base flows during the rest of the year. The Park Service's filing also uses available snow pack to determine peak flow targets each spring. Preliminary analysis indicates that their proposal is consistent with flows recommended for the endangered fishes further downstream in the Gunnison River, but more analysis using Reclamation's model will be necessary to assess their compatibility.

Finally, it is uncertain if mimicry of a natural hydrograph will restore riverine habitats sufficiently to recover the four endangered fishes. The flow regime has changed substantially over the last century, and recommendations for level and duration of spring peaks are considerably less than occurred historically. Monitoring of the physical environment should occur to ensure that important habitats continue to be created and maintained.

4.6 Implementation Guidelines

The Service, Reclamation, state of Colorado, and other interested parties in the Gunnison and upper Colorado River basins should continue to meet formally three times a year to discuss water availability and possible operating scenarios for the upcoming period. In addition, a smaller, technical team representing the Service, Reclamation, and other members of the Recovery Program should be formed to more closely monitor changing conditions in the basin than is possible in the larger forum. The team should be comprised of biologists knowledgeable about the endangered fishes and hydrologists familiar with the Gunnison and Colorado River basins. The team should meet monthly (conference calls could substitute for formal meetings in many cases) during late winter and early spring to assess changing water-availability projections and make suggestions for revisions to the proposed operation plan for the upcoming runoff period. Among other considerations, the team should recommend changes in releases from the Aspinall Unit during the pre-runoff period that will assist in meeting the target peak flows in late May or early June. During dry and moderately dry years, an important consideration should be a thorough discussion of possible trade offs between meeting the peak flow recommendations and still having sufficient water left in storage to meet minimum flows downstream from Redlands fish passage.

The Technical Team should concentrate on implementation of flows for the Gunnison River until more information is available for the Colorado River. It is recognized that flows at the Utah-Colorado state line will be determined by the combination of Gunnison River flows and flows in the upper Colorado River already provided for under the Colorado River PBO.

Recommended base flows are also based on the six hydrologic categories used to predict spring runoff. However, it is recognized that hydrologic conditions may change after runoff subsides because of above- or below-average precipitation during the base-flow period. The technical team should monitor water availability through the base-flow period and make suggestions for operational changes should water availability change dramatically.

The flow recommendations contained in this report should be implemented using adaptive management. As used here, adaptive management refers to an integrated method for addressing uncertainty in natural resource management. It is an interactive process that not only reduces, but benefits from uncertainty (Holling 1978). A number of uncertainties were identified in Section 4.5 that require further investigation and suggestions were made for further studies, monitoring, or related activities. Careful consideration should be given to resolving these uncertainties as the flow recommendations are implemented. Specific recommendations may be adjusted as more information becomes available. Further, it is impossible for a report such as this to consider all possibilities that might arise during implementation of these recommendations. The technical team will need to use their best professional judgements to make decisions when issues not identified in this report arise or uncertainties cannot be resolved. The technical team should prioritize monitoring programs or research projects that will answer questions already identified as uncertainties or other questions that arise as the flow recommendations are implemented.

Uncertainties were described in Section 4.5. Important uncertainties that should be further addressed as the flow recommendations are implemented include, but are not limited to, the following:

- Determination of the amount and location of floodplain habitat necessary for the recovery of the endangered fishes. Development of management plans for those habitats. Evaluation of the impact of high flows on human activities in the Gunnison River basin through an Environmental Impact Statement.

- Determination of the frequency (recurrence interval) and duration (number of days) that flows need to exceed ½ bankfull and bankfull discharge to maintain the suite of habitats required by the endangered fishes.

- Determination of water availability in the Gunnison River basin, with specific volumes identified for the endangered fishes.

- Determination of the amount and quality of habitat necessary to maintain populations at levels identified in the recently developed recovery goals for the four species.

Effective use of adaptive management will allow adjustments to these flow recommendations as more information is gained.

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APPENDIX A

TABLE A.1. — Critical habitat for four endangered fishes in the Gunnison and upper Colorado rivers (USFWS 1994).

Colorado pikeminnow

Colorado, Delta and Mesa Counties. The Gunnison River and its 100-year floodplain from the confluence with the Uncompahgre River in T. 15 S., R. 96 W., section 11 (6th Principal Meridian) to the confluence with the Colorado River in T. 1 S., R. 1 W., section 22 (Ute Meridian).

Colorado, Mesa and Garfield Counties; and Utah, Grand, San Juan, Wayne, and Garfield Counties. The Colorado River and its 100-year floodplain from the Colorado River Bridge at exit 90 north off Interstate 70 in T. 6 S., R. 93 W., section 16 (6th Principal Meridian) to North Wash, including the Dirty Devil arm of Lake Powell up to the full pool elevation, in T. 33 S., R. 14 E., section 29 (Salt Lake Meridian).

Razorback sucker

Colorado, Delta and Mesa Counties. The Gunnison River and its 100-year floodplain from the confluence with the Uncompahgre River in T. 15 S., R. 96 W., section 11 (6th Principal Meridian) to Redlands Diversion Dam in T. 1 S., R. 1 W., section 27 (Ute Meridian).

Colorado, Mesa and Garfield Counties. The Colorado River and its 100-year floodplain from Colorado River Bridge at exit 90 north off Interstate 70 in T. 6 S., R. 93 W., section 16 (6th Principal Meridian) to Westwater Canyon in T. 20 S., R. 25 E., section 12 (Salt Lake Meridian) including the Gunnison River and its 100-year floodplain from the Redlands Diversion Dam in T. 1 S., R. 1 W., section 27 (Ute Meridian) to the confluence with the Colorado River in T. 1 S., R. 1 W., section 22 (Ute Meridian).

Utah, Grand, San Juan, Wayne, and Garfield Counties. The Colorado River and its 100-year floodplain from Westwater Canyon in T. 20 S., R. 25 E., section 12 (Salt Lake Meridian) to full pool elevation, upstream of North Wash, and including the Dirty Devil arm of Lake Powell in T. 33 S., R. 14 E., section 29 (Salt Lake Meridian).

Humpback chub

Utah, Grand County; and Colorado, Mesa County. The Colorado River from Black Rocks in T. 10 S., R. 104 W., section 25 (6th Principal Meridian) to Fish Ford in T. 21 S., R. 24 E., section 35 (Salt Lake Meridian).

TABLE A.1. —Continued.

Humpback chub (Continued)

Utah, Garfield and San Juan Counties. The Colorado River from Brown Betty Rapid in T. 30 S., R. 18 E., section 34 (Salt Lake Meridian) to Imperial Canyon in T. 31 S., R. 17 E., section 28 (Salt Lake Meridian).

Bonytail

Utah, Grand County; and Colorado, Mesa County. The Colorado River from Black Rocks (river mile 137) in T. 10 S., R. 104 W., section 25 (6th Principal Meridian) to Fish Ford in T. 21 S., R. 24 E., section 35 (Salt Lake Meridian).

Utah, Garfield and San Juan Counties. The Colorado River from Brown Betty Rapid in T. 30 S., R. 18 E., section 34 (Salt Lake Meridian) to Imperial Canyon in T. 31 S., R. 17 E., section 28 (Salt Lake Meridian).

Table A.2. — Primary hypotheses addressed in the Aspinall Unit Investigations (McAda and Kaeding 1991a).

1. Reproductive success of Colorado pikeminnow in the Colorado River is greatest during years with maximum-annual discharges of 30,000–40,000 cfs (measured at the USGS gage near Cisco, Utah). Reproductive success is reduced in years with higher and lower peak discharge.

2. High spring flows reduce the survival of age-0 Colorado pikeminnow by reducing the growing season and thus the size of the fish entering their first winter.

3. High spring flows reduce nonnative fish populations.

4. The Gunnison River upstream from Redlands Diversion Dam contains a small, but viable Colorado pikeminnow population.

5. Providing passage around the Redlands Diversion Dam will benefit Colorado pikeminnow in both the Colorado and Gunnison rivers.

6. The Gunnison River contains habitat suitable for reintroducing razorback suckers, augmenting the Colorado pikeminnow population, and establishing a new population of humpback chub.

7. Increased flows in the Gunnison River will improve the success of razorback sucker augmentation in the Colorado River.

8. Higher flows will increase flooded areas in spring for adult fish use in both the Colorado and Gunnison rivers and will improve quality of YOY habitat in the Colorado River.

9. Higher spring flows from the Aspinall Unit will improve the ability of the Gunnison and Colorado rivers to clean spawning substrate, to maintain backwaters in nursery areas, and to maintain natural channel characteristics.

10. Reproductive success of humpback chubs in Black Rocks and Westwater Canyon will be enhanced by high spring flows from the Gunnison River. Survival of young humpback chubs will improve under a more natural flow regime.

TABLE A.3. — Results[a] of studies conducted under the Aspinall Umbrella related to hypotheses listed by McAda and Kaeding (1991a; Table A.2).

Hypothesis	Study	Results
1	McAda and Ryel (1999)	• Relative Abundance of YOY Colorado pikeminnow in autumn was highly variable. • YOY Colorado pikeminnow were most abundant in years of moderately high runoff (30,000-40,00 cfs) that had been preceded by years with high runoff (>50,000 cfs).
	Anderson (1999); Trammell and Chart (1999a)	• Density of larval Colorado pikeminnow in the drift was strongly and positively correlated with discharge. The high-flow years had the highest drift densities — Loma and Moab in 1995 and Westwater in 1993. • The lowest flow year (1994) had the lowest Colorado pikeminnow larval drift density at Westwater and Moab; lowest density at Loma was in 1996, an intermediate flow year.
2	McAda and Ryel (1999)	• YOY Colorado pikeminnow were larger in autumn of low runoff years because spawning was earlier and they had a longer growing season. • Overwinter survival of YOY Colorado pikeminnow was variable, but was highest in winters when fish were largest in autumn and lowest in winters when fish were smallest in autumn. • Size dependent mortality occurred in only one winter — when YOY Colorado pikeminnow were the smallest observed during the study. Evidence of size-dependent mortality was not found in other years, presumably because young Colorado pikeminnow were able to feed all winter and avoid starvation. • The most important predictor of age-1 Colorado pikeminnow abundance in spring was YOY abundance in autumn.
	Trammell and Chart (1999b)	• Total length of Colorado pikeminnow in autumn was positively correlated with increased over winter survival.

TABLE A.3. — Continued.

Hypothesis	Study	Results
3	McAda and Ryel (1999)	• Relative abundance of larval red shiners, fathead minnow, and sand shiners was negatively correlated with peak spring runoff (P<0.05) • Relative abundance of juvenile and adult red shiners and fathead minnow was negatively correlated with peak spring runoff (P<0.05)
	Anderson (1999); Trammell and Chart (1999a)	• Drift density of nonnative species was negatively correlated with discharge at most, but not all, drift stations. The least number of drifting larvae was collected in high flow years.
	Chart and Lentsch (1999a)	• Density of red shiners, fathead minnow, and sand shiners in Westwater Canyon were negatively correlated with peak spring runoff , but the relationships were not significant.
4	Burdick (1995)	• Five wild, adult Colorado pikeminnow were captured upstream from Redlands Diversion Dam prior to installation of fish passage. Adult Colorado pikeminnow congregated within a short reach of river during the presumed spawning season in 1993 and 1994. • Four other Colorado pikeminnow were observed, but not captured.
	Anderson (1999)	• One larval Colorado pikeminnow was captured immediately downstream from a suspected spawning site in 1994, three in 1995, and one in 1996. No sampling was done at that site in 1993, but larval Colorado pikeminnow were captured farther downstream.
5	Burdick (2001)[b]	• A total of 43 different Colorado pikeminnow have successfully ascended the fish ladder since it was completed in 1996; six of those fish ascended the ladder in two different years and one fish ascended the ladder in three different years, totaling 51 occasions.

TABLE A.3. — Continued.

Hypothesis	Study	Results
6	Burdick (1995)	• Adult Colorado pikeminnow remain within the Gunnison River year round; however, it is not yet known how many Colorado pikeminnow the river can support. • No razorback suckers were collected; however adult razorback suckers were captured in the 1980s. Suitable spawning areas and floodplain habitat (larval nursery areas) occur in the Gunnison River. • One humpback chub was collected; however, the Gunnison River does not contain habitat similar to that occupied by the other humpback chub populations in the basin.
	Anderson (1999)	• Larval Colorado pikeminnow were captured, so suitable spawning habitat is available.
7	Burdick (2000a)[b]	• Stocking of razorback suckers into the Gunnison River is ongoing. Testing of this hypothesis will require several more years to accomplish.
8	McAda and Fenton (1998)	• Limited flooded habitats were available at flows between 6,000–8,000 cfs, but substantial flooding did not occur until flows exceeded 10,000 cfs. Increase in flooded bottomland habitat leveled off at about 13,500 cfs.
	Tetra Tech (2000)[b]	• Greatest gain in flooded habitat at Escalante SWA occurred at flows of about 10,000 cfs. Dike removal at a key location could keep habitat gain at a relatively high level as river flows increase to 17,000 cfs.
9	Pitlick et al. (1999); Pitlick and Cress (2000)	• The single most important thing that can be done to maintain habitats used by the endangered fishes is to ensure that the sediment supplied to the critical reaches continues to be carried downstream. Sediment that is not carried through will accumulate preferentially in low velocity areas, resulting in further channel simplification and narrowing. • Initial motion (flows that begin to mobilize the river bed and allow fine sediments to be flushed from the substrate) occurred at flows ranging from 4,661–12,712 cfs in the Gunnison River (median = 8,073 cfs) and at 11,405–36,510 cfs in the Colorado River upstream from Westwater Canyon (median = 18,538 cfs). • Significant motion (flows that mobilize the entire river bed [≈bankfull flow]) occurred at flows ranging between 7,344–28,707 cfs in the Gunnison River (median= 14,325 cfs) and at 15,818–78,141 cfs in the Colorado River upstream from Westwater Canyon (median = 34,957).

TABLE A.3. — Continued.

Hypothesis	Study	Results
10	Chart and Lentsch (1999a)	• Humpback chub spawning success as indexed by CPE was more variable above Westwater Canyon than within Westwater Canyon proper. • Humpback chub reproductive success in and around Westwater Canyon was maximized when the Colorado River peaked near 30,000 cfs in 1996. Reproductive success was lower in years with higher and lower spring runoff. • Strong positive correlations (P<0.01) were found between the previous year's peak flow and July catch rates of YOY humpback chubs above and within Westwater Canyon. • Reproductive success was not monitored in Black Rocks.

[a] This table briefly highlights the important conclusions of the different reports specifically related to the hypotheses. Information in chapters 2 and 3 presents the results in more detail.

[b] Not funded under the Aspinall Unit Investigations umbrella.

TABLE A.4. — Estimated annual water depletions in the Colorado and Gunnison River basins within Colorado, 1986–1990. Data were compiled from the technical appendices in USBR (1997).

Depletion Type	Total Annual Depletion (af)				
	1986	1987	1988	1989	1990
Colorado River upstream from Colorado-Utah state line (excluding Gunnison River basin)					
Trans Basin Diversions	389,179	225,069	397,673	421,125	314,563
Municipal and Industrial	15,015	14,793	14,546	14,312	14,044
Irrigation	358,037	399,026	458,434	453,024	431,495
Reservoir Evaporation	31,349	31,679	31,247	30,603	28,628
Stock Pond Evaporation[a]	904	1,464	1,402	1,464	1,354
Livestock[a]	1,614	1,515	1,510	1,522	1,479
Total Depletions	796,098	673,546	904,812	922,050	791,563
Average, 1986 – 1990			817,614		
Gunnison River					
Trans Basin Diversions	1,513	1,403	692	753	699
Municipal and Industrial	4,909	4,685	4,538	4,353	4,135
Irrigation	414,786	494,188	553,341	579,423	517,244
Reservoir Evaporation	23,119	26,263	25,130	26,730	25,569
Stock Pond Evaporation[a]	736	1,192	1,140	1,192	1,102
Livestock[a]	1,314	1,233	1,229	1,238	1,204
Total Depletions	446,377	528,964	586,070	613,689	549,953
Average, 1986 – 1990			545,011		
Colorado River subbasin upstream from Colorado-Utah state line					
Total Depletions	1,242,475	1,202,510	1,490,882	1,535,739	1,341,516
Average, 1986 – 1990			1,362,625		

[a] Estimates for stock pond evaporation and livestock use were provided for the entire Colorado River mainstem within Colorado. Individual depletions for the two basins were estimated by proportion based on drainage area of the three major units — Colorado headwaters (Hydrologic Unit Codes [HUCs] 1401000–14010006, 9,730 mi^2, 38%); Gunnison River (HUCs 14020001–14020006, 7,930 mi^2, 31%); and Dolores River (HUCs 14030001–4030005, 8,250 mi^2, 32%).

TABLE A.5. — Reservoirs greater than 10,000 af storage capacity in the Gunnison River basin and in the Colorado River subbasin upstream from the confluence with the Gunnison River.

Reservoir	Year Completed	Storage Capacity (af)	
		Total	Active
Gunnison basin			
Blue Mesa	1966	940,700	748,430
Crawford	1962	14,390	13,970
Crystal	1976	25,240	12,890
Morrow Point	1968	117,190	42,120
Paonia	1962	17,461	16,527
Ridgway	1986	84,410	59,396
Silverjack	1971	13,520	12,820
Taylor Park	1937	106,225	106,225
Colorado subbasin			
Dillon	1963	257,304	254,036
Grandby	1950	540,000	465,570
Green Mountain	1943	154,645	112,850
Homestake	1963	42,880	42,670
Ruedi	1968	102,373	101,278
Rifle Gap	1967	13,602	12,168
Shadow Mountain	1947	18,400	
Vega	1959	33,800	32,900
Williams Fork	1959	93,637	
Wolford Mountain	1995	66,000	56,000

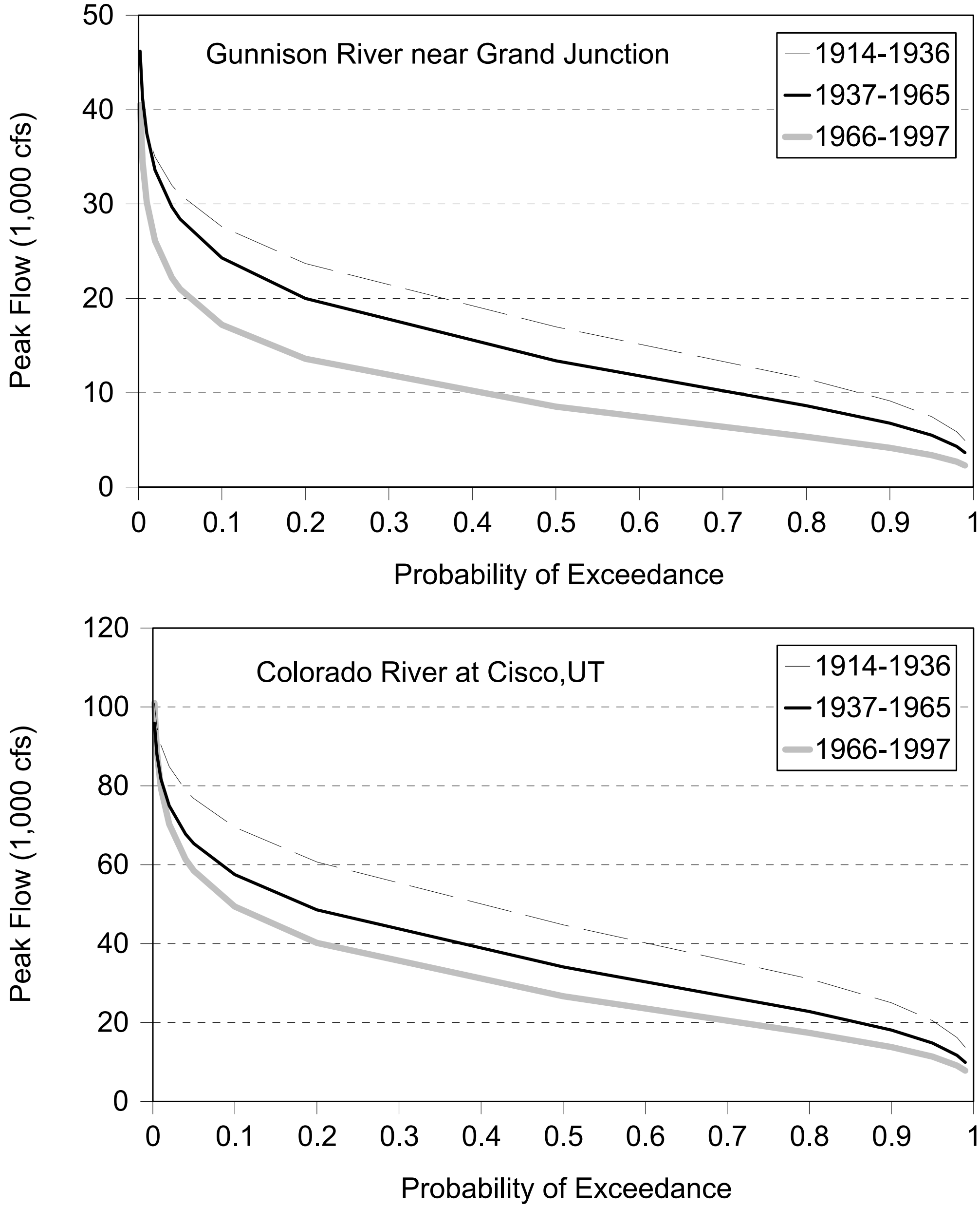

FIGURE A.1. — Flood-frequency curves for the Gunnison River near Grand Junction, Colorado (USGS gage 09152500) and the Colorado River at Cisco, Utah (USGS gage 09180500), partitioned into three water-development periods. Probabilities were calculated using a Log-Pearson Type III analysis and are presented in Table A.7.

TABLE A.6. — Changes in $Q_{1.5}$ and $Q_{2.3}$[a] over three water-development periods for the Colorado (USGS gage 09180550) and Gunnison (09152500) rivers.

Water Development Period	Colorado River near Cisco, Utah (09180550)		Gunnison River near Grand Junction, Colorado (09152500)	
	$Q_{1.5}$	$Q_{2.3}$	$Q_{1.5}$	$Q_{2.3}$
Pre Taylor Park[b]	37,200	48,200	13,900	18,500
Pre Aspinall[c]	27,900	37,200	10,800	14,800
Post Aspinall[d]	21,600	29,600	6,750	9,590

[a] Calculated using a Log-Pearson Type III analysis (USGS 1982).
[b] Colorado — 1914–1917,1923–1936; Gunnison — 1897–1899, 1902–1906, 1917–1936.
[c] 1937–1965. [d] 1966–1997.

TABLE A.7. — Changes in flood-frequency probability[a] over three water-development periods for the Colorado (USGS gage 09180550) and Gunnison (09152500) rivers.

Probability	Colorado River near Cisco, Utah (09180550)			Gunnison River near Grand Junction, Colorado (09152500)		
	Pre Taylor[b]	Pre Aspinall[c]	Post Aspinall[d]	Pre Taylor[e]	Pre Aspinall[c]	Post Aspinall[d]
0.990	13,700	9,930	7,830	4,950	3,660	2,310
0.980	16,200	11,700	9,100	5,870	4,320	2,700
0.950	20,500	14,800	11,400	7,480	5,510	3,400
0.900	25,000	18,100	13,800	9,150	6,780	4,180
0.800	31,100	22,800	17,400	11,500	8,640	5,350
0.500	44,800	34,100	26,700	17,000	13,400	8,540
0.200	60,700	48,600	40,200	23,700	20,000	13,600
0.100	69,500	57,500	49,400	27,600	24,300	17,200
0.050	76,800	65,400	58,500	31,000	28,400	21,000
0.040	78,900	67,800	61,400	32,000	29,700	22,200
0.020	84,900	75,000	70,300	35,000	33,600	26,100
0.010	90,300	81,700	79,400	37,600	37,500	30,200
0.005	95,000	88,000	88,600	40,100	41,200	34,500
0.002	101,000	95,900	101,000	43,100	46,200	40,500

[a] Calculated using a Log-Pearson Type III analysis (USGS 1982).
[b] 1914–1917,1923–1936. [c] 1937–1965. [d] 1966–1997. [e]1897–1899, 1902–1906, 1917–1936.

TABLE A.8. — Storage and outlet capacities of Blue Mesa, Morrow Point, and Crystal reservoirs.

Criteria	Reservoir: Blue Mesa	Morrow Point	Crystal
Capacity (af)			
Dead	111,200	165	7,700
Inactive	81,070	74,905	4,650
Active	748,430	42,120	12,890
Live	829,500	117,025	17,540
Total	940,700	117,190	25,240
Elevation Range (ft)			
Dead	7,186–7,358	6,747–6,808	6,547–6,670
Inactive	7,358–7,393	6,808–7,100	6,670–6,700
Active	7,393–7,519.4	7,100–7,160	6,700–6,755
Total	7,186–7,519.4	6,747–7,160	6,547–6,755
Outlet Capacity (cfs)[a]			
Powerplants (max)	2,600–3,400	4,800	1,900
Bypass	4,000–5,100	1,500–1,600	1,900–2,100
Spillway	34,000	41,000	41,350

[a] Outlet capacity varies with reservoir elevation.

TABLE A.9. — Probability of exceedance of different levels of unregulated April–July inflow to Blue Mesa Reservoir and to the Gunnison River near Grand Junction, Colorado. 1937–1997.

Blue Mesa Reservoir			Gunnison River near Grand Junction		
Unregulated Inflow (1,000 af)	Probability of Exceedance[a]	Return Interval (yr)	Unregulated Inflow (1,000 af)	Probability of Exceedance[a]	Return Interval (yr)
202	0.99	1.01	292	0.99	1.01
241	0.98	1.02	360	0.98	1.02
256	0.975	1.03	386	0.975	1.03
291	0.96	1.04	450	0.96	1.04
310	0.95	1.05	485	0.95	1.05
381[b]	**0.9**	**1.11**	**621**	**0.9**	**1.11**
428	0.85	1.18	714	0.85	1.18
481	0.8	1.25	821	0.8	1.25
520	0.75	1.33	902	0.75	1.33
561	**0.7**	**1.43**	**990**	**0.7**	**1.43**
597	0.65	1.54	1,068	0.65	1.54
635	0.6	1.67	1,153	0.6	1.67
672	0.55	1.82	1,234	0.55	1.82
709	**0.5**	**2**	**1,319**	**0.5**	**2**
746	0.45	2.22	1,406	0.45	2.22
786	0.4	2.5	1,498	0.4	2.5
828	0.35	2.86	1,599	0.35	2.86
871	**0.3**	**3.33**	**1,705**	**0.3**	**3.33**
922	0.25	4	1,831	0.25	4
975	0.2	5	1,966	0.2	5
1,046	0.15	6.67	2,151	0.15	6.67
1,123	**0.1**	**10**	**2,355**	**0.1**	**10**
1,246	0.05	20	2,696	0.05	20
1,282	0.04	25	2,798	0.04	25
1,352	0.025	40	3,003	0.025	40
1,383	0.02	50	3,095	0.02	50
1,473	0.01	100	3,366	0.01	100

[a] Derived by fitting a log-Pearson Type III distribution (USGS 1982 to the annual April–July unregulated flow data for 1937–1997.

[b] Divisions between hydrological categories are highlighted.

TABLE A.10. — Organizations whose representatives regularly attend Aspinall Unit Operation Meetings.

U.S. Government

- Argonne National Laboratory
- Bureau of Land Management
- Bureau of Reclamation
- Department of Justice
- Department of Interior Solicitor
- Fish and Wildlife Service
- Geological Survey
- National Oceanic and Atmospheric Administration
- National Park Service
- National Weather Service
- Western Area Power Administration

State and Local Government

- City of Grand Junction
- City of Delta
- Colorado Department of Agriculture
- Colorado Division of Water Resources
- Colorado Division of Wildlife
- Colorado Division of Parks
- Colorado Water Conservation Board
- Delta County Commissioners
- Delta County
- Gunnison County Commissioners

Water Users

- Colorado River Water Conservation District
- North Fork Water Conservancy District
- Redlands Water and Power Company
- Uncompahgre Valley Water Users Association
- Upper Gunnison River Water Conservancy District

Other Interested Parties

- Colorado River Energy Distributors
- Commercial Outfitters
- Grand Junction Daily Sentinel
- Gunnison Basin POWER
- Gunnison Country Times
- High Country Citizens Alliance/Sierra Club
- Land and Water Fund
- Private Citizens
- Trout Unlimited
- Upper Colorado River Commission

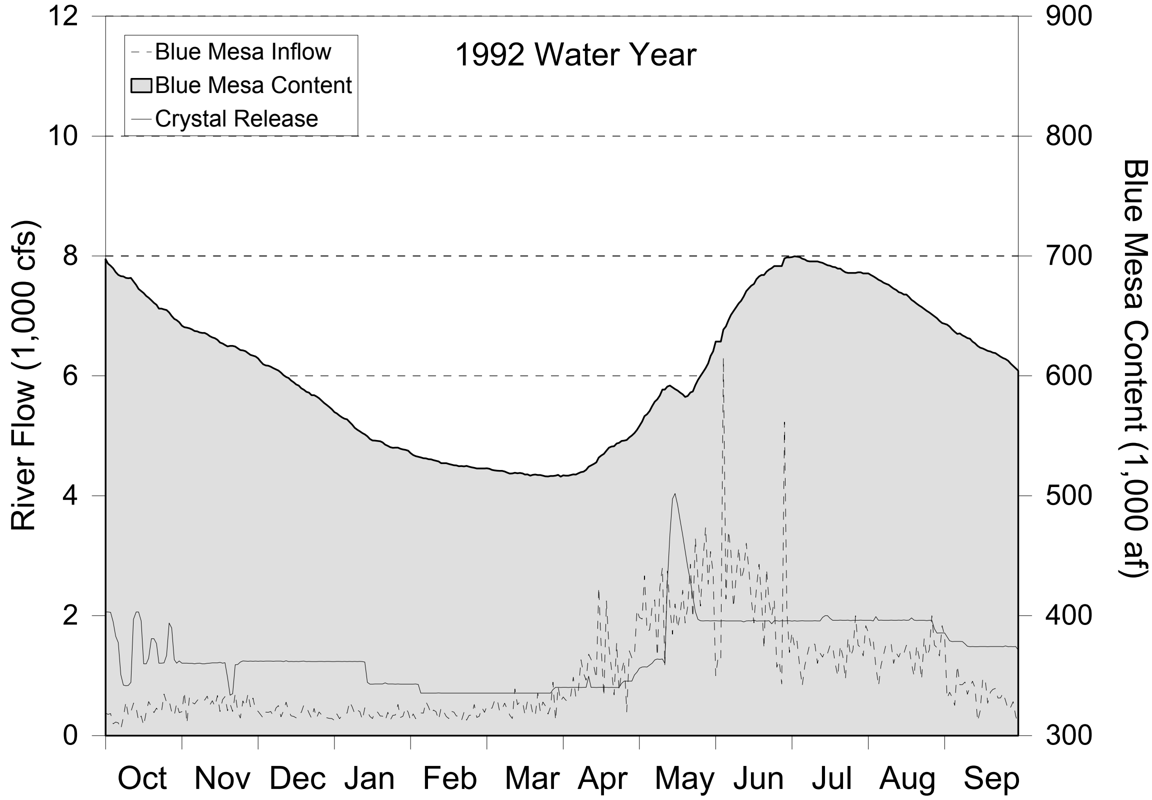

FIGURE A.2. — Relationship of water volume stored in Blue Mesa Reservoir to Blue Mesa Reservoir inflow and Crystal Reservoir releases during water year 1992.

TABLE A.11. — Summary of monthly inflow to the Aspinall Unit, 1992.

Month	Unregulated Inflow (af) Blue Mesa	Morrow Point	Crystal	Total Inflow	Average of 1961–1990	Percent of Average
January	18,000	2,000	4,000	24,000	33,000	72.7
February	20,000	2,000	3,000	25,000	30,000	83.3
March	29,000	3,000	5,000	37,000	42,000	88.1
April	66,000	11,000	12,000	89,000	101,000	88.1
May	159,000	25,000	32,000	216,000	275,000	78.5
June	152,000	16,000	26,000	194,000	368,000	52.7
July	90,000	6,000	13,000	109,000	158,000	69.0
August	60,000	4,000	10,000	74,000	77,000	96.1
September	34,000	3,000	6,000	43,000	45,000	95.6
October	28,000	2,000	4,000	34,000	45,000	75.6
November	25,000	3,000	7,000	35,000	39,000	89.7
December	22,000	2,000	4,000	28,000	33,000	84.8
Total	703,000	79,000	126,000	908,000	1,246,000	72.9

TABLE A.12. — Summary of monthly releases from the Aspinall Unit, 1992.

Month	Total Volume Released (af)	Average Release (cfs)
January	62,000	1,020
February	42,100	732
March	44,600	725
April	50,100	842
May	131,100	2,132
June	113,700	1,911
July	118,500	1,927
August	116,500	1,895
September	90,200	1,516
October	74,900	1,218
November	28,700	482
December	26,600	433
Total	899,000	

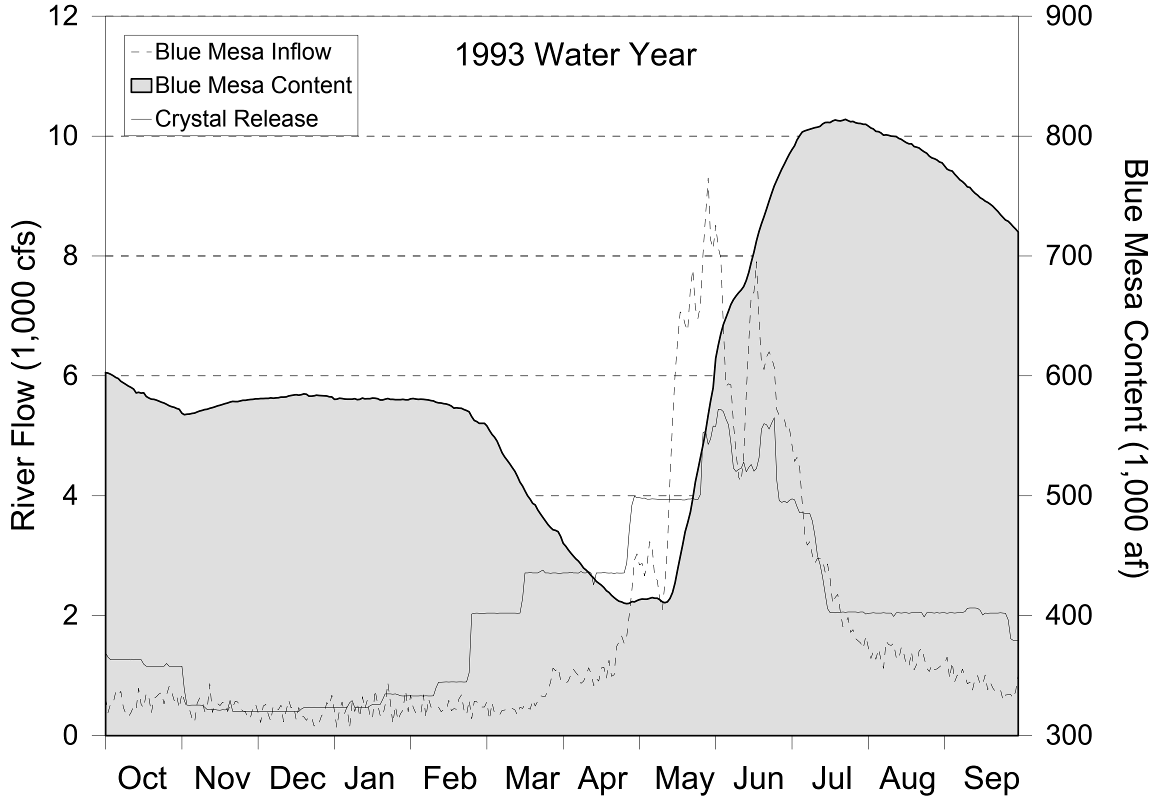

FIGURE A.3. — Relationship of water volume stored in Blue Mesa Reservoir to Blue Mesa Reservoir inflow and Crystal Reservoir releases during water year 1993.

TABLE A.13. — Summary of monthly inflow to the Aspinall Unit, 1993.

Month	Unregulated Inflow (af) Blue Mesa	Morrow Point	Crystal	Total Inflow	Average of 1961–1990	Percent of Average
January	26,000	2,000	5,000	33,000	33,000	100.0%
February	25,000	1,000	2,000	28,000	30,000	93.3%
March	35,000	8,000	12,000	55,000	42,000	131.0%
April	78,000	19,000	21,000	118,000	101,000	116.8%
May	347,000	51,000	65,000	463,000	275,000	168.4%
June	394,000	37,000	60,000	491,000	368,000	133.4%
July	168,000	8,000	18,000	194,000	158,000	122.8%
August	72,000	4,000	9,000	85,000	77,000	110.4%
September	46,000	4,000	10,000	60,000	45,000	133.3%
October	40,000	4,000	8,000	52,000	45,000	115.6%
November	29,000	3,000	6,000	38,000	39,000	97.4%
December	25,000	2,000	5,000	32,000	33,000	97.0%
Total	1,285,000	143,000	221,000	1,649,000	1,246,000	132.3%

TABLE A.14. — Summary of monthly releases from the Aspinall Unit, 1993.

Month	Total Volume Released (af)	Average Release (cfs)
January	34,600	563
February	54,300	978
March	147,600	2400
April	170,200	2860
May	255,600	4157
June	279,600	4699
July	172,000	2797
August	126,000	2049
September	118,800	1996
October	92,200	1499
November	80,700	1356
December	88,000	1431
Total	1,619,600	

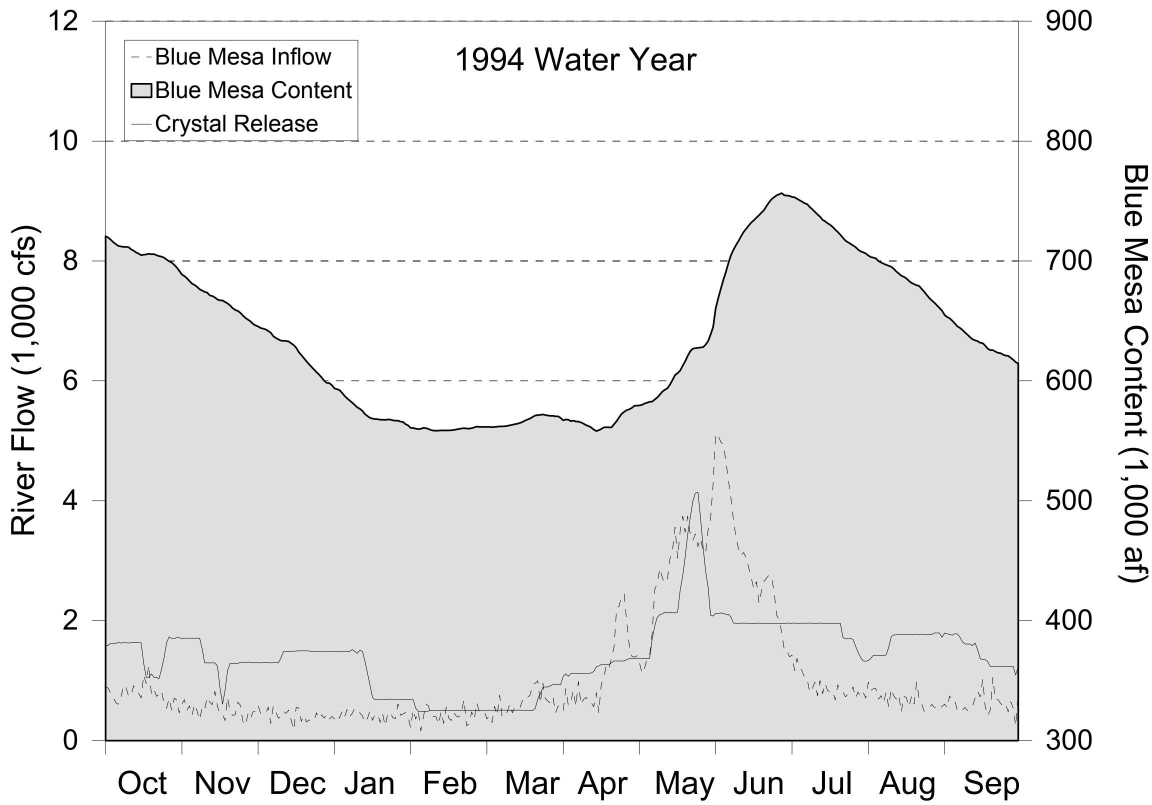

FIGURE A.4. — Relationship of water volume stored in Blue Mesa Reservoir to Blue Mesa Reservoir inflow and Crystal Reservoir releases during water year 1994.

TABLE A.15. — Summary of monthly inflow to the Aspinall Unit, 1994.

Month	Unregulated Inflow (af) Blue Mesa	Morrow Point	Crystal	Total Inflow	Average of 1961–1990	Percent of Average
January	24,000	1,000	3,000	28,000	33,000	84.8%
February	21,000	2,000	3,000	26,000	30,000	86.7%
March	37,000	3,000	5,000	45,000	42,000	107.1%
April	68,000	8,000	8,000	84,000	101,000	83.2%
May	194,000	21,000	26,000	241,000	275,000	87.6%
June	201,000	15,000	24,000	240,000	368,000	65.2%
July	45,000	3,000	7,000	55,000	158,000	34.8%
August	34,000	3,000	7,000	44,000	77,000	57.1%
September	28,000	3,000	6,000	37,000	45,000	82.2%
October	40,000	1,000	3,000	44,000	45,000	97.8%
November	28,000	2,000	4,000	34,000	39,000	87.2%
December	25,000	2,000	4,000	31,000	33,000	93.9%
Total	745,000	64,000	100,000	909,000	1,246,000	73.0%

TABLE A.16. — Summary of monthly releases from the Aspinall Unit, 1994.

Month	Total Volume Released (af)	Average Release (cfs)
January	64,000	1,041
February	29,000	522
March	39,000	634
April	73,000	1,227
May	151,000	2,456
June	118,000	1,983
July	111,000	1,805
August	103,000	1,675
September	87,000	1,462
October	60,000	976
November	42,000	706
December	48,000	781
Total	925,000	

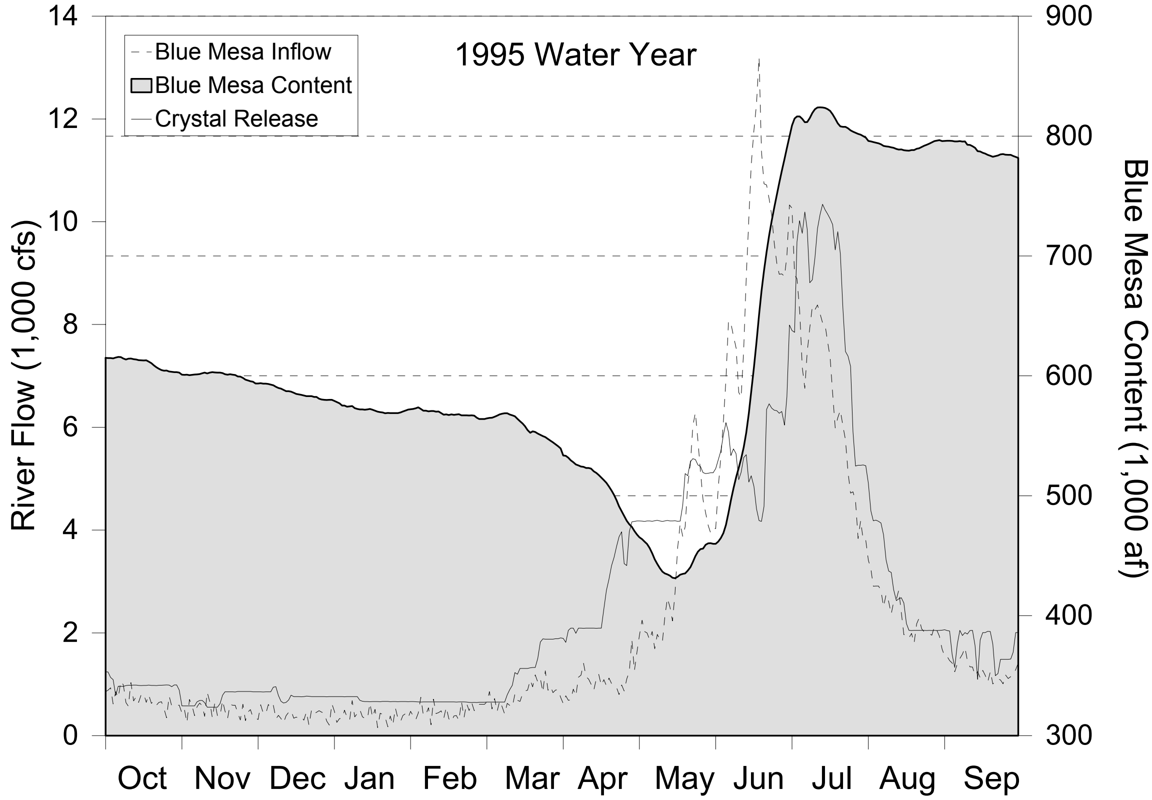

FIGURE A.5. — Relationship of water volume stored in Blue Mesa Reservoir to Blue Mesa Reservoir inflow and Crystal Reservoir releases during water year 1995.

TABLE A.17. — Summary of monthly inflow to the Aspinall Unit, 1995.

Month	Unregulated Inflow (af)			Total Inflow	Average of 1961–1990	Percent of Average
	Blue Mesa	Morrow Point	Crystal			
January	23,700	1,900	4,200	29,800	33,000	90.3%
February	25,500	2,000	3,100	30,600	30,000	102.0%
March	49,700	3,300	5,000	58,000	42,000	138.1%
April	62,600	13,000	14,100	89,700	101,000	88.8%
May	194,200	34,000	43,300	271,500	275,000	98.7%
June	579,300	56,700	92,500	728,500	368,000	198.0%
July	412,400	32,400	72,100	516,900	158,000	327.2%
August	141,000	7,500	16,700	165,200	77,000	214.5%
September	60,600	4,100	9,200	73,900	45,000	164.2%
October	44,500	3,900	8,700	57,100	45,000	126.9%
November	40,700	4,000	9,000	53,700	39,000	137.7%
December	30,600	2,700	6,000	39,300	33,000	119.1%
Total	1,664,800	165,500	283,900	2,114,200	1,246,000	169.7%

TABLE A.18. — Summary of monthly releases from the Aspinall Unit, 1995.

Month	Total Volume Released (af)	Average Release (cfs)
January	42,700	694
February	36,400	655
March	79,000	1,285
April	163,900	2,754
May	283,400	4,609
June	334,300	5,618
July	514,400	8,366
August	170,500	2,773
September	104,900	1,763
October	120,300	1,956
November	117,900	1,981
December	117,400	1,909
Total	2,085,100	

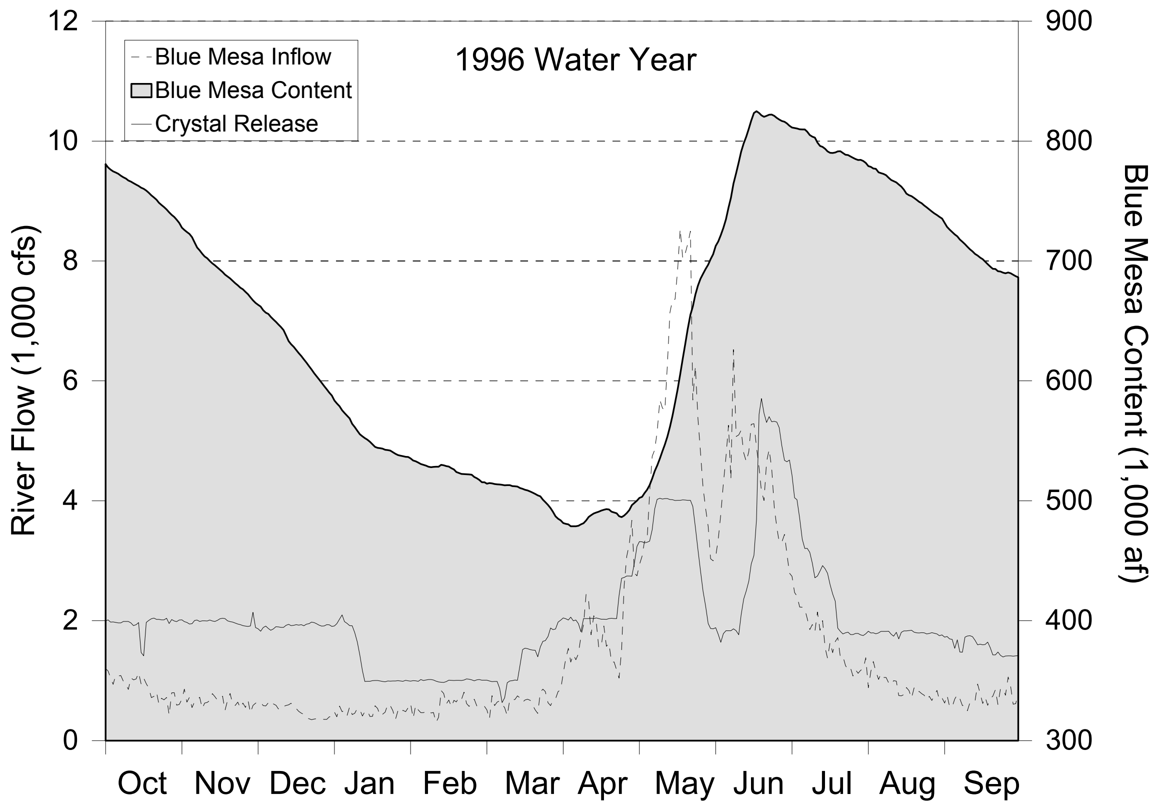

FIGURE A.6. — Relationship of water volume stored in Blue Mesa Reservoir to Blue Mesa Reservoir inflow and Reservoir Crystal releases during water year 1996.

TABLE A.19. — Summary of monthly inflow to the Aspinall Unit, 1996.

Month	Unregulated Inflow (af) Blue Mesa	Morrow Point	Crystal	Total Inflow	Average of 1961–1990	Percent of Average
January	30,000	2,000	4,000	36,000	33,000	109.1%
February	32,000	1,000	2,000	35,000	30,000	116.7%
March	39,000	4,000	6,000	49,000	42,000	116.7%
April	111,000	19,000	21,000	151,000	101,000	149.5%
May	356,000	38,000	48,000	442,000	275,000	160.7%
June	270,000	22,000	36,000	328,000	368,000	89.1%
July	93,000	6,000	13,000	112,000	158,000	70.9%
August	37,000	3,000	6,000	46,000	77,000	59.7%
September	29,000	2,000	4,000	35,000	45,000	77.8%
October	44,000	3,000	7,000	54,000	45,000	120.0%
November	39,000	2,000	4,000	45,000	39,000	115.4%
December	34,000	1,000	3,000	38,000	33,000	115.2%
Total	1,114,000	103,000	154,000	1,371,000	1,246,000	110.0%

TABLE A.20. — Summary of monthly releases from the Aspinall Unit, 1996.

Month	Total Volume Released (af)	Average Release (cfs)
January	79,000	1,285
February	58,000	1,008
March	82,000	1,334
April	132,000	2,218
May	220,000	3,578
June	208,000	3,496
July	158,000	2,570
August	110,000	1,795
September	93,000	1,563
October	79,000	1,282
November	76,000	1,286
December	78,000	1,266
Total	1,373,000	

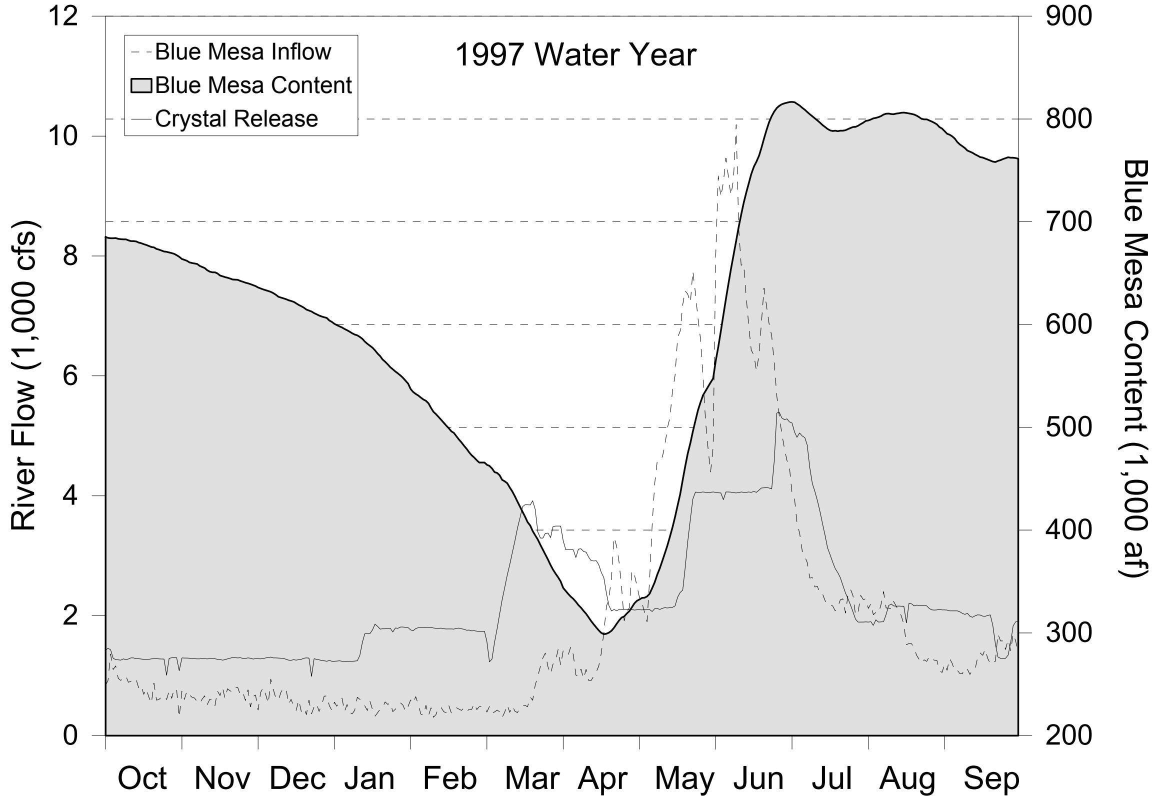

FIGURE A.7. — Relationship of water volume stored in Blue Mesa Reservoir to Blue Mesa Reservoir inflow and Crystal Reservoir releases during water year 1997.

TABLE A.21. — Summary of monthly inflow to the Aspinall Unit, 1997.

Month	Unregulated Inflow (af) Blue Mesa	Morrow Point	Crystal	Total Inflow	Average of 1961–1990	Percent of Average
January	29,000	2,000	5,000	36,000	33,000	109.09%
February	23,000	3,000	5,000	31,000	30,000	103.33%
March	43,000	8,000	12,000	63,000	42,000	150.00%
April	104,000	15,000	17,000	136,000	101,000	134.65%
May	340,000	37,000	47,000	424,000	275,000	154.18%
June	468,000	37,000	60,000	565,000	368,000	153.53%
July	150,000	8,000	17,000	175,000	158,000	110.76%
August	98,000	4,000	8,000	110,000	77,000	142.86%
September	67,000	2,000	5,000	74,000	45,000	164.44%
October	68,000	0	1,000	69,000	45,000	153.33%
November	41,000	2,000	5,000	48,000	39,000	123.08%
December	30,000	2,000	5,000	37,000	33,000	112.12%
Total	1,461,000	120,000	187,000	1,768,000	1,246,000	141.89%

TABLE A.22. — Summary of monthly releases from the Aspinall Unit, 1997.

Month	Total Volume Released (af)	Average Release (cfs)
January	97,000	1,578
February	99,000	1,783
March	186,000	3,025
April	156,000	2,622
May	177,000	2,879
June	258,000	4,336
July	203,000	3,301
August	128,000	2,082
September	111,000	1,865
October	116,000	1,887
November	107,000	1,798
December	118,000	1,919
Total	1,756,000	

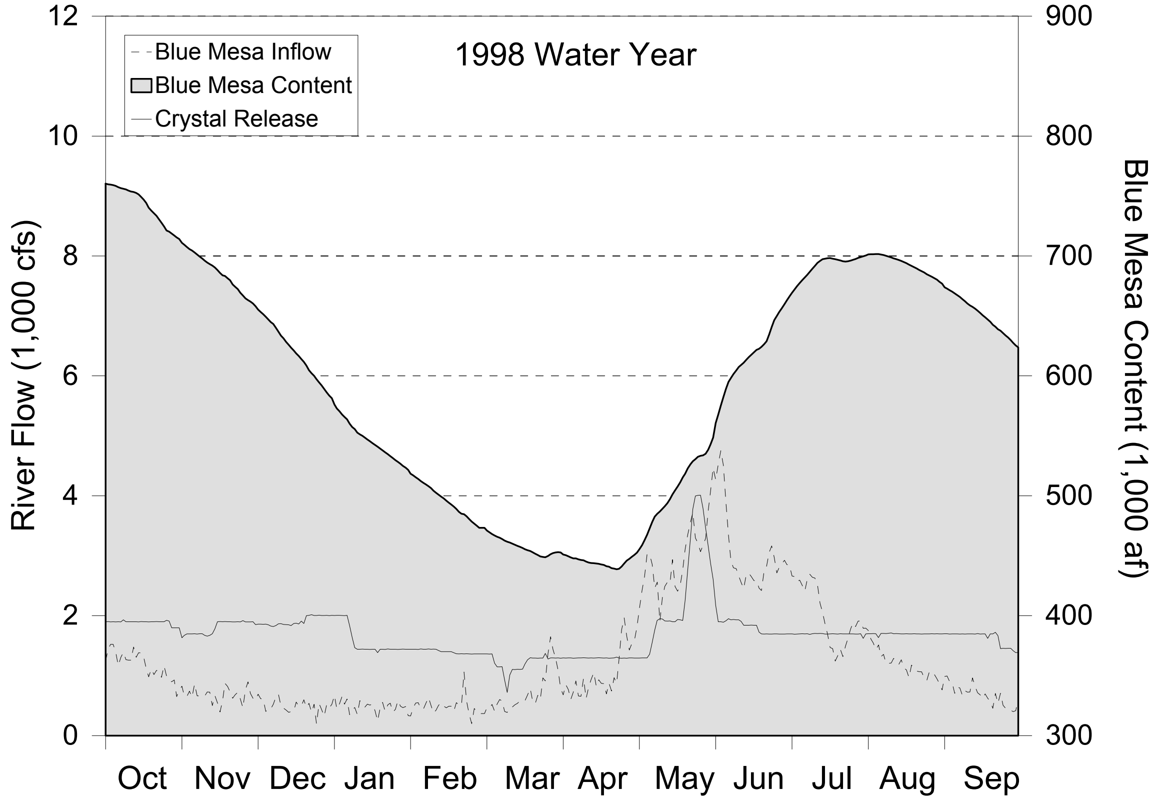

FIGURE A.8. — Relationship of water volume stored in Blue Mesa Reservoir to Blue Mesa Reservoir inflow and Crystal Reservoir releases during water year 1998.

TABLE A.23. — Summary of monthly inflow to the Aspinall Unit, 1998.

Month	Unregulated Inflow (af) Blue Mesa	Morrow Point	Crystal	Total Inflow	Average of 1961–1990	Percent of Average
January	30,000	2,000	6,000	38,000	33,000	115.2%
February	26,000	3,000	4,000	33,000	30,000	110.0%
March	43,000	4,000	7,000	54,000	42,000	128.6%
April	60,000	9,000	10,000	79,000	101,000	78.2%
May	189,000	29,000	37,000	255,000	275,000	92.7%
June	193,000	15,000	25,000	233,000	368,000	63.3%
July	123,000	5,000	11,000	139,000	158,000	88.0%
August	62,000	2,000	5,000	69,000	77,000	89.6%
September	30,000	2,000	4,000	36,000	45,000	80.0%
October	42,000	2,000	4,000	48,000	45,000	106.7%
November	36,000	2,000	5,000	43,000	39,000	110.3%
December	24,000	2,000	4,000	30,000	33,000	90.9%
Total	858,000	77,000	122,000	1,057,000	1,246,000	84.8%

TABLE A.24. — Summary of monthly releases from the Aspinall Unit, 1998.

Month	Total Volume Released (af)	Average Release (cfs)
January	69,000	1,561
February	78,000	1,404
March	75,000	1,220
April	77,000	1,294
May	146,000	2,374
June	108,000	1,815
July	104,000	1,691
August	104,000	1,691
September	97,000	1,630
October	80,000	1,301
November	46,000	733
December	49,000	797
Total	1,033,000	

Table A.25. — The frequency of years with sediment transport capacity (STCI) adequate to flush sediment from different macrohabitats within the Gunnison River. Data were compiled from Tables II–VI in Milhous (1998).

Time Period	Percentage of Years with flushing flows	Average STCI	Percentage of 1897–1936 STCI
STCI adequate to flush the surface of the bed; critical discharge, 13,171 cfs			
1897–1899, 1902–1906, 1917–1936	68	46.1	100
1940–1965	50	20.8	45
1968–1995	21	6.8	15
STCI adequate to flush gravel from pools; critical discharge, 17,000 cfs			
1897–1899, 1902–1906, 1917–1936	50	20.5	100
1940–1965	31	7.4	36
1968–1995	14	1.4	7
STCI adequate to scour side channels; critical discharge, 7,415 cfs			
1897–1899, 1902–1906, 1917–1936	93	122.3	100
1940–1965	85	70.0	57
1968–1995	57	31.7	32

TABLE A.26. — Frequency and duration of instream flows necessary to maintain habitat at the Dominguez Flats reach (RM 38) of the Gunnison River. Data were compiled from Tables VII and VIII in Milhous (1998).

Objective	Target Size (mm)	Transport Mode	Critical Discharge (cfs)	Duration		Frequency (Years)
				Days	STCI	
Flush Riffles	4.7	Suspended	12,535		16	33%
Flush River	2.0	Wash	12,499	4		50%
Maintain Riffles	0.5	Wash	953			100%
Clean pools of gravel		Bed	17,000		6	33%
Scour side channels	1.0	Wash	7,415		20	66%

TABLE A.27. — Average summer water temperature[a] (average of mean-daily temperatures, °C) of the Gunnison River near Delta, Colorado and near the mouth at Grand Junction, Colorado. Water temperatures at other sites in the upper Colorado River basin occupied by Colorado pikeminnow are given for comparison.

Year/Month	Gunnison River at Delta, Colorado	Gunnison River at Grand Junction, Colorado	Yampa River at Government Bridge, Colorado	Green River at Browns Park, Colorado	Green River at Jensen, Utah
1992					
Jun	16.1	17.9	16.9	16.9	19.0
Jul	17.6	20.3	19.1	17.3	19.5
Aug	17.5	20.6	20.0	16.3	19.7
Sep	15.4	17.9	15.8	13.8	17.0
1993					
Jun		13.2	12.6		15.5
Jul		18.1	17.2		19.7
Aug		19.3	19.6		
Sep		16.1	15.2		
1994					
Jun		19.0	18.0		19.0
Jul		21.7	21.1	16.7	21.2
Aug		21.8	21.9		21.1
Sep		17.1	16.4		17.3
1995					
Jun	11.4	12.0	11.9	13.1	14.9
Jul	13.5	13.7	16.1	14.6	18.7
Aug	17.7	19.5	20.7	16.5	21.7
Sep	15.5	17.0	16.5	14.4	17.1
1996					
Jun	14.8				16.4
Jul	17.7			17.8	22.3
Aug	18.6		21.1	16.0	20.7
Sep	15.0		15.5	13.2	15.8
1997					
Jun	13.2	12.6	13.8	11.8	15.9
Jul	16.2	18.1	19.6	15.0	19.6
Aug	17.7	19.7	20.0	15.9	20.3
Sep	15.8	17.1	16.8	14.8	17.1

TABLE A.27. — Continued.

Year/Month	Gunnison River at Delta, Colorado	Gunnison River at Grand Junction, Colorado	Yampa River at Government Bridge, Colorado	Green River at Browns Park, Colorado	Green River at Jensen, Utah
1998					
Jun	14.3	16.2		12.0	15.3
Jul	19.0	21.7		15.4	21.1
Aug	18.0			15.8	20.1
Sep	15.7			15.0	17.8
1999					
Jun	15.0			11.7	14.9
Jul	18.4			16.3	20.5
Aug	16.5			16.6	20.4
Sep	14.6			13.3	15.8
2000					
Jun	16.5	19.5	16.2	14.7	18.2
Jul	18.6	21.6	22.1	17.5	22.1
Aug	18.1	20.8	20.9	15.9	21.5
Sep	15.7	17.0	14.8	13.4	15.9
		Mean; 1992, 1995, 1997, 2000[b]			
Jun	14.3	15.5	14.7	14.1	17.0
Jul	16.5	18.4	19.2	16.1	20.0
Aug	17.8	20.2	20.4	16.2	20.8
Sep	15.6	17.3	16.0	14.1	16.8

[a] Data were compiled from thermographs maintained by the Recovery Program (G. Smith, unpublished data).

[b] Mean of years with complete data sets for all five sites.

TABLE A.28. — Range of flow variables that were significantly correlated with autumn CPE of red shiner, sand shiner, fathead minnow, and native species other than Colorado pikeminnow (combined). Data were excerpted from Table A-1 in McAda and Ryel (1999).

Flow Variable	Minimum	Maximum
Peak Flow[a]	9,670	69,500
Average High Flow[b]	7,701	54,629
Monthly Average		
April	2,497	21,180
May	4,070	42,087
June	6,320	46,340
July	2,779	30,080
August	2,230	11,396
September	2,808	7,403
Number of Days that Flow Exceeded:		
5,000 cfs	34	360
10,000 cfs	0	136
15,000 cfs	0	95
20,000 cfs	0	78
25,000 cfs	0	66

[a] Mean-daily flow on the highest day of the year.

[b] Mean of mean-daily flows for 15 days on either side of the highest day of the year.

TABLE A.29.—Factor loadings of flow variables for factors 1 and 2. Table 10 in McAda and Ryel (1999).

Variable	Factor 1	Factor 2
Average High Flow[a], Previous Year	-0.575	0.766
Average High Flow, Current Year	-0.944	-0.241
Mean April Flow	-0.637	0.620
Number of Days that Flow Exceeded 5,000 cfs	-0.864	0.160
Number of Days that Flow Exceeded 20,000 cfs	-0.895	-0.036
Number of Days that Flow Exceeded 30,000 cfs	-0.892	-0.360
Number of Days that Flow Exceeded 40,000 cfs	-0.864	-0.384
Number of Days that Flow Exceeded 50,000 cfs	-0.788	-0.361
Number of Days that Flow Exceeded 60,000 cfs	-0.737	-0.232
Mean May-June Flow, Current Year	-0.963	-0.143
Mean July-August-September Flow, Current Year	-0.837	-0.409
Mean May-June Flow, Previous Year	-0.629	0.735
Mean July-August-September Flow, Previous Year	-0.669	0.618

[a] Mean of mean-daily flows for 15 days on either side of the highest day of the year.

TABLE A.30. — Mean number of days that mean-daily river flow remained within 90 and 95% of the highest mean-daily flow of the year as measured by USGS river gages on the Colorado River near Cisco, Utah (09180550) and on the Gunnison River near Grand Junction, Colorado (09152500).

Hydrological Category	Colorado River		Gunnison River	
	90%	95%	90%	95%
Dry	4.0(2)[a]	2.5(2)	2.0(2)	1.5(2)
Moderately Dry	4.8(8)	2.3(8)	3.8(10)	2.1(10)
Average-Dry	3.7(6)	2.0(6)	4.5(4)	1.8(4)
Mean of all Years ≤ Average-Dry	4.3(16)	2.2(16)	3.8(16)	1.9(16)
Average-Wet	3.0(2)	3.0(2)	2.7(3)	1.7(3)
Moderately Wet	4.8(9)	3.0(9)	3.7(9)	2.6(9)
Wet	5.0(2)	4.5(2)	3.0(1)	1.0(1)
Mean of all Years ≥ Average-Wet	4.5(13)	3.2(13)	3.4(13)	2.3(13)
Mean of all Years	4.4(29)	2.6(29)	3.6(29)	2.1(29)

[a] Mean of years in category (number of years in category).

TABLE A.31. — Probability of exceedance of different levels of unregulated April–July inflow to the Colorado River at the Colorado-Utah state line (1958–1997) and at Cisco, Utah (1937–1992).

Colorado-Utah state line			Cisco, Utah		
Unregulated Inflow (1,000 af)	Probability of Exceedance[a]	Return Interval (yr)	Unregulated Inflow (1,000 af)	Probability of Exceedance[a]	Return Interval (yr)
1,151	0.99	1.01	1,068	0.99	1.01
1,337	0.98	1.02	1,267	0.98	1.02
1,407	0.975	1.03	1,342	0.975	1.03
1,571	0.96	1.04	1,521	0.96	1.04
1,659	0.95	1.05	1,619	0.95	1.05
1,991	**0.9**	**1.11**	**1,990**	**0.9**	**1.11**
2,212	0.85	1.18	2,239	0.85	1.18
2,456	0.8	1.25	2,519	0.8	1.25
2,639	0.75	1.33	2,729	0.75	1.33
2,835	**0.7**	**1.43**	**2,957**	**0.7**	**1.43**
3,007	0.65	1.54	3,157	0.65	1.54
3,190	0.6	1.67	3,371	0.6	1.67
3,366	0.55	1.82	3,577	0.55	1.82
3,547	**0.5**	**2**	**3,790**	**0.5**	**2**
3,733	0.45	2.22	4,010	0.45	2.22
3,929	0.4	2.5	4,242	0.4	2.5
4,141	0.35	2.86	4,493	0.35	2.86
4,364	**0.3**	**3.33**	**4,759**	**0.3**	**3.33**
4,629	0.25	4	5,074	0.25	4
4,909	0.2	5	5,409	0.2	5
5,301	0.15	6.67	5,877	0.15	6.67
5,725	**0.1**	**10**	**6,385**	**0.1**	**10**
6,447	0.05	20	7,248	0.05	20
6,665	0.04	25	7,509	0.04	25
7,106	0.025	40	8,035	0.025	40
7,307	0.02	50	8,274	0.02	50
7,905	0.01	100	8,984	0.01	100

[a] Derived by fitting a Log-Pearson Type III distribution (USGS 1982) to the annual April–July unregulated flow data for 1958–1997 at the state line gage and for 1937–1992 at the Cisco gage.

[b] Divisions between hydrological categories are highlighted.